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IMPROVED HF DATA NETWORK SIMULATOR

Harris Corporation

Marvin C. Baker

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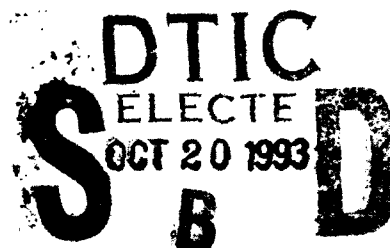
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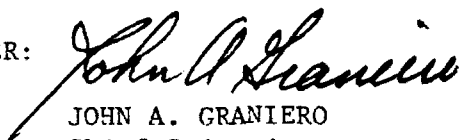
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13. ABSTRACT (Maximum 200 words) This effort advances the state-of-the-art in networking for both data/voice communications in the HF (2- 30 MHZ) band. This is contained in a PC portable simulation called the Improved HF Data Network Simulator (INS). INS algorithms emphasize a decentralized, distributed architecture and interoperability for both military and civilian air-land-sea mobile users. Up to 100 users are contained in up to 10 nets that make up one network. The intended radii for the nets/network are 400 and 4000 miles respectively.

Technical issues addressed are improved HF networking, LQA techniques, LPD/LPE waveforms for OPSEC, and frequency hop (FH) frequency management. The INS provides the means for configuring a network to any user's protocols/architectures with node, path and network results available over the 24 hour time period of the propagation model (IONCAP).

To receive the INS, you must complete a STATEMENT OF TERMS AND CONDITIONS FOR RELEASE OF USAF OWNED DEVELOPED SOFTWARE. Contact the RL program manager to obtain this.

A Phase II effort titled "Adaptive Network Controller (ANC)" will put the Phase I algorithms into use on real-time over-the-air HF networks to demonstrate the improvement in HF communications.

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ABSTRACT

This report covers the details of an effort to advance the state-of-the-art in networking for both digital data and digital voice communications in the HF (2-30 MHz) band. The approach integrated adaptive routing, integrated data transmission and channel evaluation, selectable quality of service, and HF channel modelling. The techniques were implemented and tested in a user friendly, PC based simulation called the Improved HF Data Network Simulation (INS).

This work focused upon interoperability for either military or civilian air-land-sea mobile users that comprise an HF network with a totally decentralized, distributed architecture. Up to 10 small nets with radii of 400 miles comprise one large network with a radius of 4000 miles and up to 100 members at any given time. Technical issues addressed here were improved HF networking, LQA techniques, LPD/LPE waveforms for OPSEC, and frequency hop (FH) frequency management. The INS provides the means for configuring a network to any user's protocols/architectures with node, net, path, and network results available as a print-out over the 24 hour time period of the IONCAP based propagation model (twelve, two hour increments).

The PC requirements are MS-DOS 2.1 or later, 640 RAM, 20-40 MB HD, EGA graphics, and MS (serial) mouse. A typical 20 node, 9 net architecture simulation consumes approximately 1 MB of hard disk space and executes in 1 minute on a 10 MHz PC.

Request forms to obtain the User's Manual and the INS may be obtained by contacting the RL focal point.

1.0 Background

This final report documents the final products and conclusions reached for the Improved HF Data Network (IHFDN) program. Separate documents (Software Design Document, Software User's Manual, and Software Programmers Manual) document the software simulation (INS) that resulted from this 2½ year study.

The IHFDN program was undertaken, because of the need to apply networking techniques to High Frequency (HF; 2-30 MHz) communications. Networking has been applied to many forms of telecommunications, with great success. Networks such as ARPANET, TYMNET, IBM's SNA, Digital Equipment Company's DNA, and commercial telephone networks, to name a few, are well documented in the literature, and used daily in the "real world". However, networking techniques have only recently been applied to HF communications, primarily through the work of amateur radio enthusiasts, utilizing commercially available AX.25 packet controllers.

The goal of the IHFDN program was to raise HF networking to a level which would be suitable for military users, who are accustomed to: frequency hopping, link quality analysis (LQA), automatic link establishment (ALE), operational security (OPSEC), full duplex operation, digital voice and data, communication from moving platforms, geographically diverse network topologies, low probability of detection/exploitation (LPD/LPE), and the many uncertainties of HF communication. Through the application of networking techniques to HF communications, it is felt that users will be able to achieve cost effective, reliable, transportable communications systems which are independent of landlines, commercial networks, satellites, and fixed site repeater stations.

The "ground rules" of the IHFDN come from three sources: the IHFDN statement of work (SOW) as supplied by Rome Labs, the HF environment, and the state of the art of HF communications in the areas of LQA, networking and LPE/LPD. The sections below cover these ground rules, so that later sections may build upon them to construct the IHFDN.

1.1 The HF Medium

The HF medium is a key element of the IHFDN, and its unique nature shapes every aspect of network design. A thorough understanding of HF communications is essential to the design and investigation of the IHFDN.

1.1.1 HF Requirements

The SOW contains several aspects of the network which must be viewed from an HF perspective. These are:

- · · modes of propagation: ground wave, skywave
- · channel parameter measurement: SNDR, multipath, fading, etc.
- · geographic size: 4000-mile radius circular area

Each of these aspects impact the HF communication, but before discussing their impact, a basic review of HF communication is provided.

1.1.2 HF Propagation

There are two basic modes of HF propagation: ground wave, and skywave (Figure 1.1.2-1). Groundwave propagation results when radio waves travel in or near the earth's surface. Groundwave can travel through the ground, ("surface wave"), reflect off the ground ("reflected wave"), directly from transmitter to receiver (line-of-sight, or LOS) , or slightly beyond the horizon due to diffraction in the troposphere (beyond line of sight, or BLOS). For the aircraft based IHFDN, all modes except the surface wave are applicable.

Skywave occurs when radio waves are refracted by the ionosphere, allowing communication close in, as well as far beyond the horizon. Due to the large geographic size of the IHFDN, skywave is an essential mode of communication. Because skywave depends on ionospheric refraction, it is important to understand this phenomena.
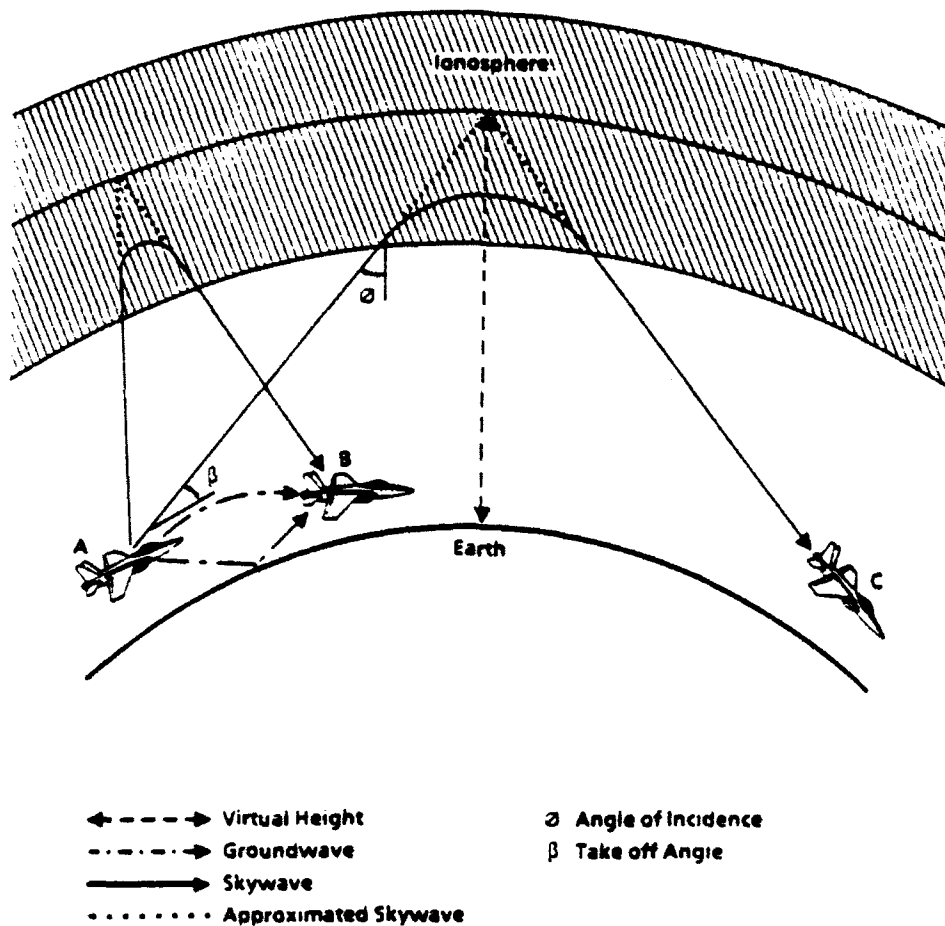
Figure 1.1.2-1 Propagation Modes

Skywave propagation of HF signals between widely separated stations depends on the refraction of radio waves by charged regions in the ionosphere, beginning about 100 km above the earth. The electron density in these regions depends strongly on radiation from the sun, and hence exhibits both diurnal and seasonal changes. In addition, it shows a strong correlation with sunspot numbers and the intensity of solar radiation at 2800 MHz (10.7 cm). These variations are somewhat predictable. Certain unpredictable cosmic events - such as magnetic storms, solar flares - may cause HF blackouts, as can large terrestrial events such as volcanic eruptions and atomic explosions. The ionosphere exhibits a remarkable ability to recover from such disturbances, usually within a few hours.

1.1.2.1 HF Modes

By understanding groundwave paths, and skywave ionospheric refraction, it is possible to identify the modes of propagation which must be considered for the IHFDN. The list below describes HF propagation modes in more detail. Non-refractive modes groundwave have been divided into LOS, and BLOS. The skywave modes (which utilize ionospheric refraction) have been divided into NVIS, and Oblique one hop, and Oblique multi-hop.

- Line of Sight (LOS). Straight-line propagation between stations is possible. The line-of-sight distance between two aircraft above a spherical earth varies from about 550 miles when both are at 50,000 feet, to about 175 miles when both are at 5000 feet. The corresponding values of free-space (spreading) loss range from 45 to 55 dB.

- Beyond Line of Sight (BLOS)-. Straight-line propagation is not possible. Over-the-horizon propagation depends on diffraction of the transmitted wave. Beyond line of sight range, estimated by the 4/3 earth radius method, gives approximate BLOS distances (for the two-aircraft in the LOS example) as 630 and 200 miles, respectively. The spreading losses are about 56 and 46 dB, respectively.

  LOS and BLOS links depend on direct propagation between stations i.e., ionospheric propagation is not involved. They may suffer from interference between the direct ray, and NVIS sky waves or ground reflections.

- Near vertical Incidence of Sky-wave (NVIS) . Useful when ground obstructions prevent LOS propagation between nearby stations. This mode depends on ionospheric refraction of sky waves at near vertical incidence. The transition from NVIS to single-hop oblique incidence propagation may be arbitrarily placed at the takeoff angle of one radian. Assuming a vertical height of reflection of 250 km, it follows from the path geometry and the secant law that the maximum NVIS range is about 310 miles. The path loss is relatively constant with respect to range because the vertical height of reflection normally exceeds the ground range.

- Oblique Incidence (1-hop). Medium distance over-the-horizon skywave propagation. The ground range for this mode depends on the take-off angle and the height of reflection. The minimum range is limited by the lack of high-angle rays at the transmitting station. The maximum range for low-angle rays is limited

to about 1600 miles. The useful frequencies for single-hop operation may be several times the critical frequency, depending on path length.

- Oblique Incidence (Multi-hop) Long distance propagation involving tandem sky wave hops with reflections at intermediate points. The only option for very long HF links is multiple-hop operation using intermediate reflection points for the incident ray paths. The ray path for an 8000-mile link may have five or more hops, with intermediate reflections occurring at the earth's surface or at charged regions in the lower ionosphere. Such paths are complex and difficult to predict, and the path loss may be very large. On the positive side, the delay spread is smaller than on short links. The transmitting station radiates energy 2-n many directions, so that multiple ray paths can satisfy the requirements of single-hop links. Of these, only a few will satisfy the requirements of a multi-hop link.

Figure 1.1.2-2 summarizes the points discussed in this section. The distances covered by each propagation mode are presented in chart form. LOS and BLOS modes are represented by the span of maximum range for aircraft stations at altitudes from 5K to 50K feet. The minimum range of communication approaches zero in LOS mode. NVIS has been arbitrarily defined in terms of take-off angles between the vertical and 1 radian for take-off angles below one radian the mode is defined as oblique. The minimum range for NVIS is arbitrarily placed at about 90 miles, approximately the distance to the radio horizon at 5K feet. Below this limit, LOS or BLOS modes may be available if the terrain allows. Airborne transmitters cannot suppress LOS or groundwave transmission by a suitable antenna design, as ground station can; therefore, the NVIS and LOS modes may compete over this common coverage area.

DISTANCE IN HUNDREDS OF STATUTE MILES
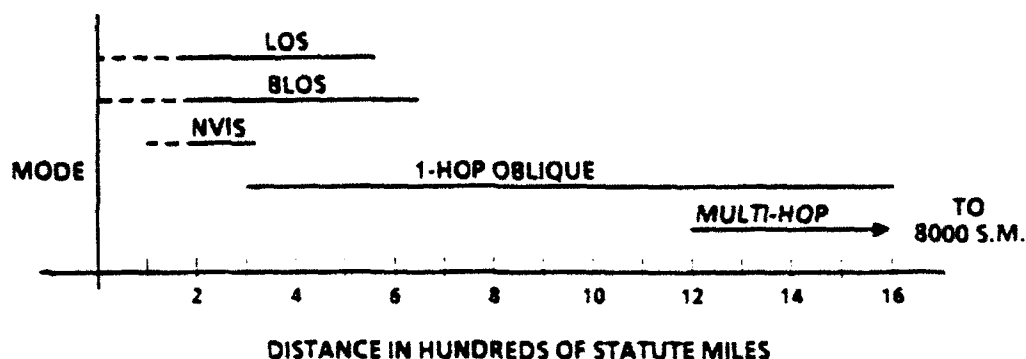
MODE	RANGE (S.M.)	TIME PROPAGATION (MSEC)	LOSS SPREAD
LOS	175 - 550	1.92 - 2.50	2.3 dB
BLOS	200 - 630	1.99 - 3.83	5.7 dB
NVIS	90 - 310	1.73 - 1.97	1.1 dB
1-HOP	310 - 1600	1.5ˉ - 8.58	12.8 dB
N-HOP	1200 - 8000	6.76 - 43.0	16 + 6 (N-1) dB

Figure 1.1.2-2
Typical Operating Mode Characteristics
For Virtual Height of 250 KM.

1.1.3 Propagation Time

Each of the propagation modes discussed above will result in a different propagation time of the radiated signal. Propagation time affects the functions of the IHFDN which require accurate time synchronization. Knowledge of propagation time must be utilized during on-air time-of-day exchanges, and conferencing, for example, to allow a given station to communicate with both distant (multi-hop) and close (LOS) stations. One-direction propagation time can be measured by measuring the time from local site message transmission to distant site message acknowledgement, subtracting processing time, and dividing by two.

1.1.4 Geographic Size

The statement of work defines a network comprising a circular area with a radius of 4000 statute miles. HF is an ideal medium to use for this size of network, but it is important to know how size affects network design. To get a conception of the extent of this size network, let the radius be defined in terms of a 4000-mile arc lying on a great circle that passes through the north pole, and let one end of the arc be placed at the pole. The other end of the arc will lie at about 32 degrees north latitude (approximately the latitude of Tucson), and the area swept by the arc amounts to more than 46 million square miles - nearly 24 percent of the earth's surface. The maximum separation between points in this area is 8000 miles, and the propagation time between them at maximum separation is about 43 milliseconds. Uniform HF link characteristics cannot be expected over such large areas for several reasons:

    a.   Path losses vary widely.

    b.   Propagation conditions vary as the day-night boundary moves through the area.

    c.   Electrical disturbances, both manmade and natural, differ at widely separated stations.

    d.   A variety of HF propagation modes must be utilized to ensure point-to-point connectivity between all net members.

1.1.5 Summary of HF Medium

All of the HF factors listed in sections above had a profound impact on network design. All communication links will be different from each other, occasionally non-existent, and continually varying with time. This places a burden on the network design to compensate through institution of extremely robust, flexible, adaptive features. Though we can learn from existing techniques for networking and packet-radio (the vast majority of which are for LOS and wireline networks), it is important to realize that HF makes many of the existing techniques non-applicable. The IHFDN design was based on modification of existing techniques, and create new innovative techniques which are explicitly applicable to the IHFDN.

1.2 Link Quality Analysis

1.2.1 LQA Requirements of the IHFDN

Several key LQA concepts permeate the SOW, and they are:

1. Hardware Integration: All LQA algorithms and techniques must utilize the same communications equipment as the normal frequency hopped traffic.

2. HF Parameters: LQA is used to measure channel conditions within given ranges of interest.

3. Waveform Integration: LQA waveforms must appear like, and be concurrent with typical frequency hopped data traffic; LQA is performed while units are active or non-active.

4. Application of channel measurements: Channel conditions are used to estimate symbol error rates, change operating frequencies, and perform adaptive functions.

5. BER Estimates: Fast, reliable bit error rate estimation methods are required.

1.2.2 HF Channel Characteristics

The HF channel characteristics are determined by the radio equipment and the HF path. In general, the radio equipment sets the noise bandwidth, transmitted power, adjacent channel rejection, and certain forms of distortion, the most notable being delay and amplitude distortion and frequency offsets. In principle, these characteristics are relatively stable and predictable, and the equipment can be designed to compensate for them. The HF path characteristics are typically random variables, and are far more difficult to deal with.

Signal-to-Noise Ratio (SNR). The design of HF links begins with the receiving site noise, which establishes the minimum useable signal level at the receiver. The receiver noise figure is seldom a factor because it is well below the level of atmospheric noise. The quasi-minimum noise (QMN) model provides an estimate:

$$N = 60.3 - 27.3 \log_{10} f$$

where N is the noise power in 1 Hz bandwidth, expressed in dB relation to thermal noise, and f is in MHz. At 10 MHz the QMN model gives -106 dBm noise in a 3 KHz bandwidth.

For a system that requires 10 dB signal-to-noise ratio, it follows that the required signal power at the receiving antenna output is -96 dBm. An estimate of the transmitter power is then obtained by accounting for antenna gains and losses, and for propagation loss. The signal-to-noise density ratio (SNDR), is defined as the ratio: (average power of the signal components) divided by (average noise power density in one Hz bandwidth) at the output. SNDR can be converted to SNR for a given noise bandwidth by subtracting 10 log (noise bandwidth). For instance, a 45 dB SNDR is the same as the 10 dB SNR if the noise bandwidth is 3 KHz (10 log 3000 = 35 dB).

Other HF parameters besides SNR can best be understood by viewing a narrowband channel model developed in the 1960's, and formalized in widely distributed Department of Commerce reports published in the 1970's (see figure 1.2.2-3). The model comprises a tapped delay line, each tap representing one multipath component of the HF signal; tap multipliers, each driven by an independent complex fading function; and a combiner which produces the simulated channel output. The output can be evaluated in terms of delay spread (the delay spanned by the delay line taps), the fading bandwidth (the double-sided RMS bandwidth of the complex fading functions), and SNDR. In practice these parameters are non-stationary random variables that can be defined by sampling at rates commensurate with the fading bandwidth. The relationship between model parameters and channel quality must be determined experimentally. In general, it can be said that channel quality varies directly with SNDR, and inversely with fading bandwidth and delay spread.
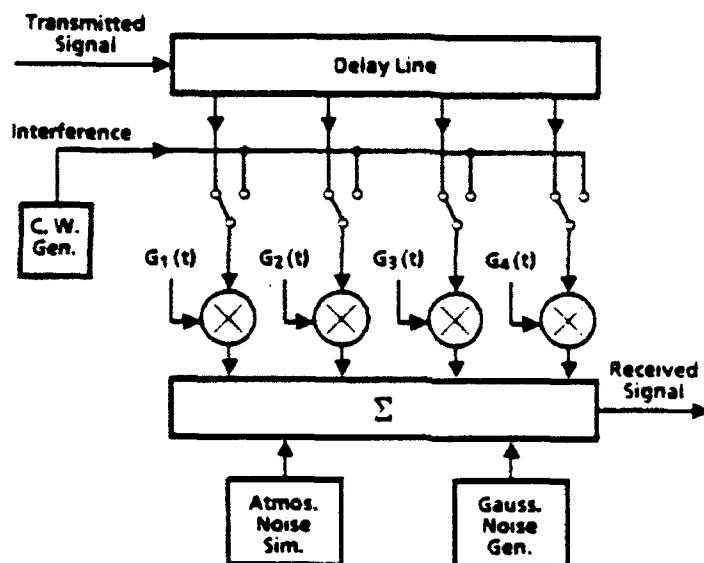
Figure 1.2.2-3 Block Diagram Model of an HF Channel

Fading Rate and Bandwidth. Fading on HF channels is due to variation of ionospheric conditions with time. Typical fading bandwidths are less than one Hz. A relationship between fading rate and two-sided fading bandwidth (f_B) has been developed (Rice, BSTJ 1948) for Rayleigh fading:

$$f_R = 0.74f_B$$

where the fade rate f_R is the number of crossings/second. Here, a crossing is an excursion of the tone envelope across the median level in a downward direction. Formally, the fading bandwidth is defined in terms of the RMS bandwidth of the fading function G(t) (see figure 1.2.2-3)

Impulse Response. The arrival of multiple propagation paths at the receiver is modeled by

several taps, each with a different gain function. The output of each multiplier will exhibit flat fading - i.e., all frequency components of the signal fade simultaneously - with Rayleigh distributed envelope amplitude and uniformly distributed phase. The multipath signal at the model output will exhibit selective fading - i.e., spectral notches will occur at particular frequency components that depend on the delay spread and tap gain functions. Typical multipath delay spreads are less than 2 ms.

Doppler. Doppler frequency shifts due to the ionosphere are generally small (less than 1 Hz) in comparison with frequency offsets in SSB radio equipment (about 1 Hz/MHz) or Doppler shift due to relative motion between the receiver and transmitter (about 1.2 Hz/ (mach MHz) . The worst-case Doppler shift between airborne stations closing at mach 2 is about 72 Hz when the transmitting frequency is 30 MHz. The worst-case doppler tracking rate occurs when the relative range vector is shortest. For two aircraft on reciprocal courses such that the shortest range vector is 15 km, the maximum doppler rate is about 3.5 Hz/second. The IHFDN specification for Doppler shift is up to 50 Hz.

Channel Model Parameters. The statement of work specifies that network members will expect to operate in HF paths characterized by delay spreads up to 5 milliseconds and fading bandwidth (Doppler) spreads ranging from 0 .2 5 to 2 Hz. By CCIR standards, such path conditions would be considered as "poor", or worse. Since these channel conditions are challenging, it is of interest to know that conditions worse than these may be encountered in everyday operation. A review of the literature will show that HF conditions worse than those specified have been observed. Davies (Department of Commerce NBS monograph 80, 1965) provides a chart showing the maximum expected values of delay spread versus path distance for HF channels. The chart shows, somewhat surprisingly, that the expected values of maximum delay peak at about 8 milliseconds for 100 km paths, with a broad minimum at about 5000 km. However, there are at least two regions in the world where worse conditions have been reported.

Polar region: The magnetic field of the earth interacts with the solar wind, causing rapid changes in the ionosphere that are made visible in part by the aurora borealis. The effects on radio waves include:

- rapid changes in the critical frequency, at rates up to 10 MHz/hour
- excess loss due to polar cap absorption (PCA)
- excess loss due to auroral zone absorption (in a ring roughly centered on the magnetic pole)
- flutter fading at high rates (up to 100 Hz) due to auroral backscatter
- unpredictable changes in refraction from sporadic-E and F layers
- excess path delays caused by non-great-circle modes propagating via irregular charge distribution in the F layer

Trans-equatorial region: Non-great-circle modes (also called equatorial spread-F) are also produced by side reflections from irregular charge distributions in the F layer between 15 degrees north and south latitudes. They depend on sun angle, and so exhibit both diurnal and seasonal variations. These regions may on occasion produce excess path loss, delay spread approaching 15 milliseconds, or fading bandwidths in excess of 50 Hz. The probability that such extreme conditions will be encountered depends in part on the geography of the path. Experimental evidence suggests that these effects can be compensated for by adaptive communication terminals using LQA methods.

1.3 Networking

1.3.1 Networking Requirements

The HF networking defined in the SOW has the following important characteristics which must be considered:

- frequency hopped system

- up to 100 nodes, aircraft (hence quite mobile), 3 to 10 active nodes spread over 4000-mile radius circle

- nodes are part of predetermined nets, there is traffic within the nets and between members of different nets

- dynamic connectivity over HF channels as a function of time, frequency, and distance

- LQA and operational traffic must use the same radio resources at each node

- voice and data services must be provided to the users (75,300,1200, 2400 bps), voice is packetized (digitized)

- voice conferencing is required, 3 to 10 participants, less than 30 minutes in duration, and listeners can interrupt at any time

- The network management function must be distributed, this requires that the central director concept be de-emphasized.

- Network design should be accomplished with a knowledge of existing Air Force networks, and results should be feasible, practical, and potentially applicable to

these networks.

1.3.2 Study Emphasis

The emphasis of the IHFDN is in a direction that maximizes the network throughput. The maximization of network throughput is a complex tradeoff between a large number of factors. In order to provide reliable voice and data services to a network of up to 100 users, it is necessary to conduct LQA measurements over the HF channel resources available to the network. The frequency management algorithm must adapt to the change in propagation so that the network services will be robust with respect to dynamic channel variations. The LQA measurement quality improves as the amount of time and/or bandwidth allocated to the process is increased, but fewer resources are then available for data and voice services and hence can decrease throughput.

When an LQA measurement is made, it is made at the receiver, so the transmitter does not know the result of the measurement. In order to use the LQA measurements effectively, it is necessary to distribute the results Of the LQA measurements throughout the network. This process provides the distributed data base for organizing the network in real time and consumes channel resources. It is this process of distributing the database of LQA measurements in the form of a connectivity database that provides robustness with respect to node failures. The LPD/LPE requirement may also be costly in terms of network throughput. As transmitter power is increased to increase the network throughput, the signal detectability increases.

1.3.3 Concepts for the IHFDN

This section presents concepts for HF networks and assess their viability for the problem described above. A preliminary evaluation of their suitability for the IHFDN is presented.

1.3.3.1 Network Architecture

Several network architectural concepts are considered in this section. One concept for network organization is the centralized director concept. In the centralized director network, a single node is responsible for network management. All connectivity measurements obtained using LQA and requests for link establishment are sent to the centralized director. The radio resources are extremely busy at a centralized director. The network which incorporates the centralized director concept is extremely vulnerable to the connectivity changes to and from the centralized director, and to failure of a single node, the centralized director.

The distributed flat network is one in which every node is considered to be equal as far as network management. In this approach, there is no centralized director. Sufficient connectivity

information must be distributed to the nodes to determine the best frequencies to use and accomplish routing for multihop traffic. The flat netv·ork organization will generally not scale very well with the number of nodes. The N^2 growth of node pairs for LQA measurements and the growth of routing tables and network management link overhead can not be accommodated on the sparse HF link resources.

A propagation dependent hierarchical network is one in which the network nodes are organized into nets, (Figure 1.3.3.1). If the nodes are all equal and are not part of smaller functional groups, the determination of net membership, who is in charge, and intercluster gateways can be done based solely on the connectivity database. The hierarchical network structure has the virtue that the coordination and management of the nets results in a smaller number of nodes. The N^2 growth of LQA transmissions, network management link overhead, and routing tables can be overcome by hierarchical organization.

If the network nodes are predetermined to be in functional groups, then this must be the first consideration in the formation of nets. This organization is called a fixed hierarchical network. If the nodes which have been predetermined to be in a functional group are fully connected, then they can be organized as a net in the SOW sense. If the predetermined group of nodes are not fully connected, then they must be organized into 2 or more nets. In any case, the groups or nets or clusters are determined, they are fully connected.

Net 1   Net 2   Net 3
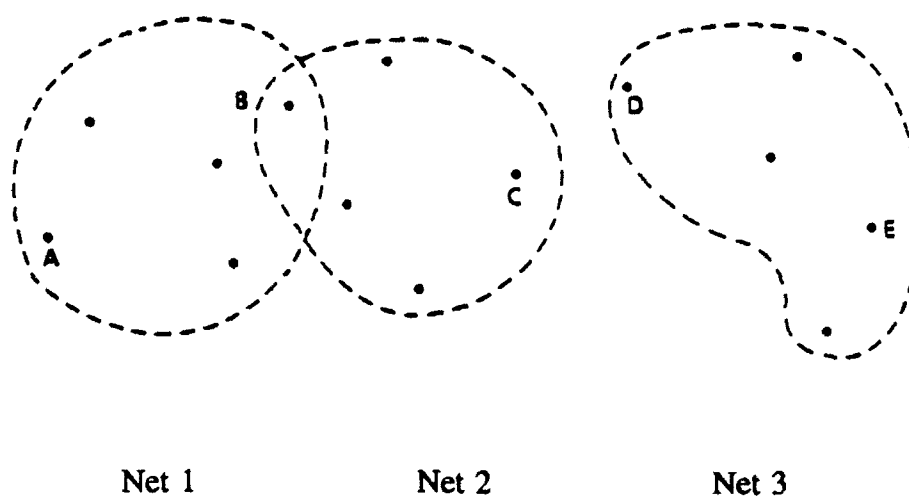
Figure 1.3.3-1 A Network Comprised of Nets

1.3.3.2 Channel Access

Analysis of channel access methods abound in the literature. These are usually sensitive to the assumptions about traffic characteristics and assume full and static connectivity between net members. If the cooperating nodes of a multiple access net hear each other unreliably, then the multiple access protocols must be modified to be robust with respect to this unreliability.

There are four access methods commonly used in Networks: synchronous, time division multiple access (TDMA), asynchronous frequency hopping multiple access (FHMA), frequency hopping code division multiple access (CDMA) carrier sense multiple access (CSMA), and two other techniques.

TDMA is implemented by providing a single hopping sequence for all net members, which forms a "channel" within the subset of the HF band. The channel is then shared by scheduling fixed predetermined time intervals during which each node is permitted to transmit. If the users are low duty cycle and bursty, then most of the time slots are unused and the utilization efficiency of the channel is poor. If users have a great deal of data to pass, TDMA may not offer enough access to the channel, due to its rigid time shared method. If nodes join or depart the net, the schedule must be changed, which is difficult in a distributed environment. This form of channel sharing is not suitable for real time voice service.

FHMA exploits the pseudo-random, asynchronous properties of frequency hopping sequences. In a net configuration, it is possible for a number of simultaneous frequency hopped transmissions to be active and, if the number of users is small, their mutual interference to be negligible . Unfortunately, as the number of users increases, the mutual interference increases, as users collide more often on common channels. FHMA has the advantages of low complexity of coordination between users, and provides continuous access to the channel which is desirable for real time voice.

CDMA uses orthogonal frequency hopping sequences which when perfectly synchronized have no collisions and thus do not interfere with each other. The orthogonality holds only if the two sequences received at a node are perfectly synchronized. Even if the transmitter sequences are perfectly synchronized, the received sequences may not be due to propagation delay differences, and the CDMA becomes nearly equivalent to the asynchronous FHMA. It is therefore important to avoid or at least account for propagation delay in CDMA schemes.

CSMA is one of a class of contention based multiple access approaches which are well suited for scenarios in which there are many bursty users. All nodes share a frequency hopping

sequence, and a node who does not hear the carrier of any node is free to access the channel. There is a period of vulnerability equal to the propagation delay between two nodes during which two nodes do not hear each other and begin transmitting. Their transmissions collide and depending on the receiver structure may be lost. If packet lengths are long compared to propagation delays the CSMA scheme is reasonably efficient. In a net environment, where all nodes are connected using the allocated subset of the HF band, the net members can directly hear each other's carrier. There is a "hidden terminal" problem when a transmitting node, "A", can not hear the transmissions of a second node, " B". A transmits when it thinks the channel is clear, but actually interferes with B'S transmission. The hidden terminal problem is prevalent in HF due to the non-uniformity of HF propagation. CSMA is not well suited to a real time voice service, it adapts well to changes in the user community. For the purposes of the study effort, the CSMA seems attractive for management functions or data functions rather than voice.

Method	Advantages	Disadvantages
TDMA	Fixed, known allocations, stable configuration.	Requires accurate timing, restricted communication time, low efficiency with few users, poor reaction to heavy load.
FHMA	No difficult timing, simple procedures.	Poor reaction to heavy load, low efficiency, collisions occur.
CDMA	No collisions.	Requires accurate timing, requires code distribution.
CSMA	No difficult timing, simple procedures, highly flexible.	Collisions with "hidden terminal", low efficiency, instability.
SAMA	Highly stable, no difficult timing.	Requires lower data rates, code distribution.
Reservation	Reacts to heavy loads, most efficient, allows priority.	Complex procedures, requires accurate timing.

Table 1.3.3-1 Access Methods

1.3.3.3 Routing

The routing function arises when multiple relays are required for communication and there are several potential paths. Point-to-point routing uses only one path for the message to be routed. This method minimizes network disruption, but is vulnerable to single point failure. Multiple path point-to-point routing (Figure 1.3.3-2) allows messages to move along several distinct paths, increasing the reliability of message transfer.

Net 1   Net 2   Net 3
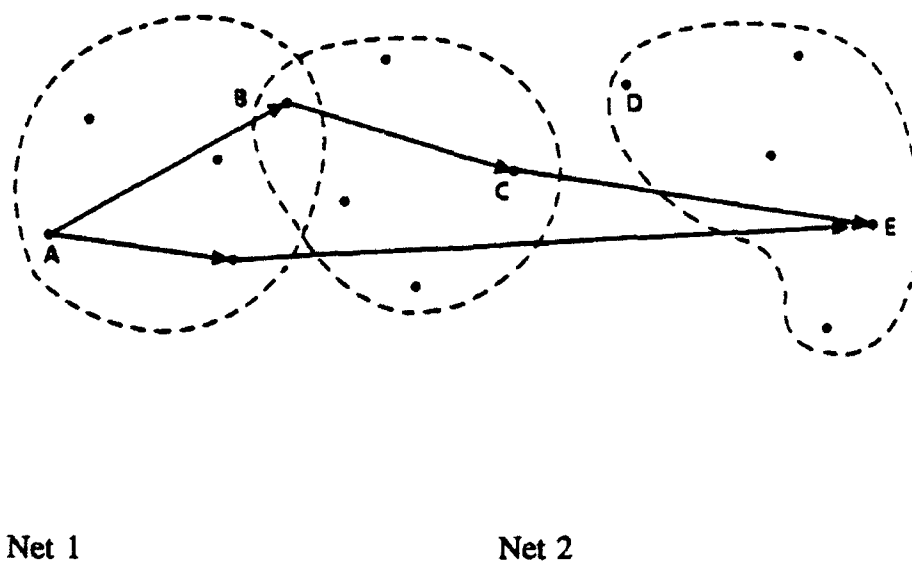
Figure 1.3.3-2 Multiple Path Point-to-Point Routing

In multicast routing, a message is sent to some subset of the members of the entire network or all members of the network (Figure 1.3.3-2). An optimization criterion for the multicast routing is to minimize the number of repeats while covering the network.

Net 1   Net 2   Net 3
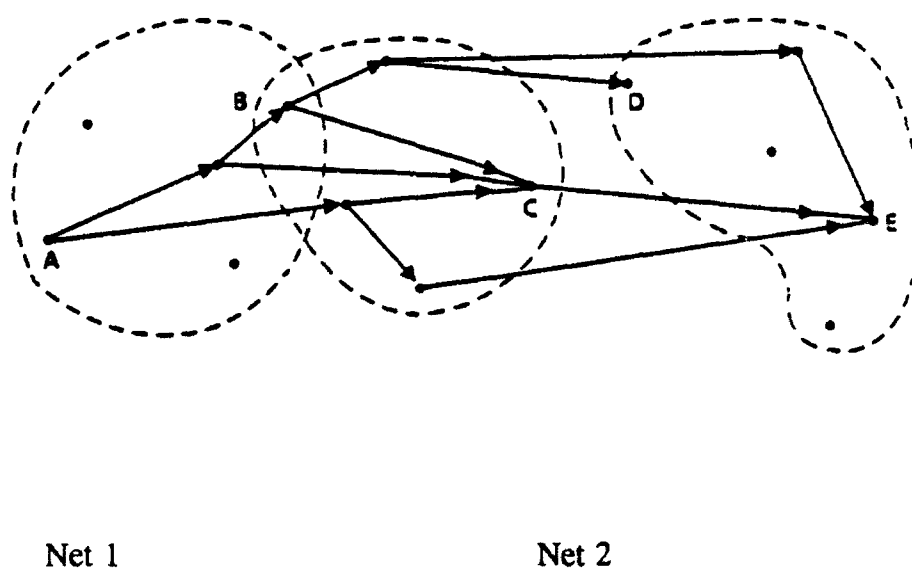
Figure 1.3.3-3 Multicast Routing

1.3.3.4 Distribution of Connectivity Information

Connectivity information derived from LQA measurements must be summarized and distributed for use in the adaptive routing, frequency management, and connectivity. In general, the connectivity data base contains an estimate of the quality of HF propagation band between all node pairs as a function of carrier frequency. In an HF network, since the nodes are physically separated by propagation delays of tens of milliseconds, and the HF channel reliability is significantly less than perfect, the resulting connectivity data bases throughout the network are incomplete, error-prone, and delayed. The mechanism for distributing the data base can be enhanced, but this requires more channel bandwidth. An alternative is to design the adaptive frequency management algorithms and adaptive routing algorithms to be more robust with respect to inconsistencies, errors and latency.

The IHFDN exploits all transmissions for the purpose of LQA measurements. In this approach, all transmissions use the same waveform, and have a spectral content which can be used to extract channel quality. In addition, if only up to 10 nodes are active at any time, then there will be many nodes who are idle in that they are not supporting data transport services. This idle time will be used for LQA measurements. Regarding OPSEC, it is desirable that near-continuous transmission marks the role of the node in terms of both network organization and military operations.

1.3.3.5 Priority Interrupt

Priority interrupt is a method of assigning network assets to specific users when the net becomes overloaded or degraded due to loss of some assets. Current network users are ranked to determine who must leave the network if conditions require a reduction in the number of users.

Priority may be used either with preemption or without preemption. Preemptive priority enables a user or users already being served to be disconnected in order to accommodate a high priority user. Non-preemptive priority places the high priority user at the head of the queue to be served as soon as capacity is available. With preemptive priority service schemes, the high priority users are unaffected by the lower priority users. With non-preemptive priority service, the high priority users are affected by virtue of the fact that service to low priority user is continued to completion.

1.4 LPE/LPD

The IHFDN must provide communication services while maintaining a low probability of detection (LPD) and a low probability of exploitation (LPE).

Detection occurs when an observer becomes aware that some form of communication is in progress. Once detected, waveforms may be exploited, even without demodulation, providing information concerning the location of the transmitter or receiver, the network function being performed (OPSEC), and the data rate being used (if communications are underway). Although it will never be possible to communicate while simultaneously prohibiting detection and exploitation, there are waveform features which make detection and exploitation more difficult.

1.4.1 LPE/LPD Waveforms

A serial HF waveform fits very nicely in a system requiring LPD and LPE. Harris has gained considerable experience in the design and testing of serial HF modems over the past ten years (specifically, the RF-5254. A constant parameter of the Harris serial modem waveform is that it transmits 8-ary PSK 'chips' at a 2.4 kb/s rate independent of the underlying modulation type or data rate. The most recent version can support up to 2.4 kb/s data with moderate rate frequency hopping using a 3 kHz instantaneous bandwidth. Operational modes vary from coherent detection of 8-PSK to non-coherent detection of orthogonal signals at 75 bps, all with an identical spectral signature.

1.4.2 LPE/LPD Requirements

The LPE/LPD requirements of the IHFDN as stated in the SOW are:

- frequency hopping

- adaptive data rate and transmit power with prioritized users, and throughput determination

- constant signature waveforms

1.4.3 Key Issue

LPD: The key issues in providing a low detection probability are to reduce the radiated power and to rapidly change the features of the waveform.

Reducing the radiated power (EIRP) forces an interceptor to observe the waveform longer before detecting its presence, or alternatively, restricts the geometrical areas in which detection is possible. A waveform that is efficient at communicating (in terms of required Eb/No) and can tolerate significant interference levels is the most significant element in lowering the required EIRP. Of course, a transmission scheme that emits only the required power levels is necessary to take full advantage of this efficiency. Another aspect to minimizing EIRP is to use only those frequencies which propagate to the receiver, which can only be accomplished by adaptively selecting 'good' frequencies. This requires continuous LQA and an effective network control structure to utilize this information. Rapidly changing the features (time, frequency or waveshape) of the signal make it appear more like its background (noise) and, therefore, lowers its probability of being detected. Changes in frequency imply frequency hopping while randomization with time might imply pseudo-random hop dwell times. Direct spreading the signal before hopping changes the waveform. The objective of feature randomization is to have the apparent signal 'disappear' before the interceptor can detect its presence.

LPE: It is possible to define waveforms which conceal the link characteristics even though detected, thereby preventing exploitation. Communication over HF links, especially via skywave, makes it virtually impossible to preclude detection by geometrically advantaged interceptors, thus a waveform having an LPE characteristic is highly desirable. The keys to LPE are to make the spectral signature constant (independent of link activity) and to randomize signal features as much as is possible. A constant signature means that all link activities result in signals with a similar spectral density, power, duration, etc., so that an uninformed observer cannot infer what the link is doing. Feature randomization makes the signal change rapidly enough to prevent analysis and/or demodulation by unauthorized receivers.

There is a fundamental conflict between the concepts of maximum throughput and LPD or LPE. Link throughput is maximized by making the signal stand out from its environment so that the intended signal from interference. This is accomplished by relatively high signal-to-noise ratios, predictable signal parameters and using the highest data rate possible with the allotted bandwidth. All these actions are diametrically opposed to the goal of LPE and LPD techniques which attempt to make the signal blend in with its environment by lowering power spectral density, introducing unpredictable features and lowering the data rate to channel bandwidth ratio. While some actions may be taken to enhance LPE/LPD characteristics without impacting throughput, most will require that link throughput be sacrificed to obtain a lower probability detection and/or exploitation.

1.4.4 LPE/LPD Methods

The following paragraphs describe in more detail some techniques which may be used to provide LPE and/or LPD, the costs and benefits of each and their suitability to the IHFDN.

1.4.4.1 Frequency Hopping

The objective of frequency hopping is to use a particular (3 kHz) frequency and then move off before the signal may be exploited and, if possible, before being detected. Frequency hopping complicates both the intercept and the jamming/spoofing problem. Detection is more difficult since it is not sufficient to examine the right frequency; it must be observed at the right time for the right duration. If hopping is accomplished faster than a few hops per second, it becomes extremely difficult to separate a hopped signal from the usual signal level variations found on HF. This is only effective, however, if the revisits to a single frequency are space by a period of seconds (as a minimum). Spoofing a frequency hopped signal is hard since the receiver is apt to be looking at a different frequency by the time a spoofer's signal reaches it.

Detection theorists argue that hop rates of several hundred hops per second are necessary to thwart detection and frequency follower jamming. However their arguments do not show an appreciation of how severe an environment the HF bands really are. Observation of only a few milliseconds of an HF waveform is almost certainly not enough to discern a single sideband AM signal from a direct spread waveform that is frequency hopped. Power level and multipath smear in many of the thousands of 3 kHz bands fluctuates significantly at any point in time, making the start of a frequency hop difficult to discern. Since the HF bands are heavily used, on the order of 50% in the US (80% in Europe) there are always many signals to sort through. The result is that hop rates in excess of a few hops per second make detection extremely unlikely on HF. Overall, frequency hopping is an effective technique for enhancing waveform LPD/LPE characteristics and will be useful on all links.

1.4.4.2 Direct Spreading

The objective of direct spreading is to lower the signal's power spectral density without degrading performance. Direct spreading precedes frequency hopping and always expands the signal bandwidth.

Benefits from direct spreading are improved performance in the presence of jamming (both intentional and unintentional), a lower power spectral density making detection more difficult, and another dimension (i.e. spreading code) for multiple access. Direct spreading makes it easy to maintain a constant signature independent of link activity. The cost of direct spreading is principally a reduction in link throughput rate, since it always expands the signal bandwidth and

the ultimate channel bandwidth is constrained to be no more than 3 KHz. Direct spreading can also complicate the modem acquisition and tracking functions since they will be performed at a lower carrier-to-noise ratio.

Direct spreading is useful on all links where the data rate to instantaneous bandwidth is significantly less than unity. A cover sequence, identical to the spreading sequence, may be used in conjunction with higher rate links to provide a uniform signature, but this is not really a spreading function.

1.4.4.3 Power Control

Power control has the objective of radiating the minimum energy level required to maintain the desired communications service. In one form, power levels might adapt in response to changing channel conditions or link data rate. Another approach is to set power levels prior to some mission or task, according to expected communication rate, range and channel characteristics.

Power control helps the interceptor problem in two ways. It reduces EIRP levels which forces a detector to make longer signal observations, reduces the region from which detection is likely, and reduces the self-interference levels presented to other members of a multiple access network. Reduced self-interference may permit adequate communication performance with reduced signal or higher interference levels. The cost of power control is that the amplifiers must have variable output capability, and to be effective, power control requires accurate channel estimator or, if adaptive, accurate LQA with a reliable control channel algorithm.

Adaptive power control is not a new concept, but its application (especially to HF) has many pitfalls. A pre-requisite for power control is that LQA information be available. Since short term characteristics of individual HF channels can change significantly over 5 to 10 minute intervals, this not only implies accurate measurements but also timely ones. Next there must be a method of moving the LQA data from the observer to the transmitter (or controller if different). Both LQA and measurement communication are overhead functions that decrease the networks capacity for communicating data. Finally there must be a carefully developed algorithm for evaluating the required power level. Experience has taught us that there are two aspects which must not be ignored in developing power control algorithm: adaptive power control presents another opportunity for spoofing and the algorithm must fail in a fashion that does halt communications when inputs are inaccurate or missing. The latter of these conditions was derived from hours of network simulation which demonstrated that control data is certain to be incorrect or missing occasionally if it must be communicated via HF links. Final concern is to minimize the probability that a spoofer can exploit adaptive power control to evaluate the effectiveness of various spoofing strategies.

Coupled with adaptive power control is the ability to adaptively change bit rates. Reducing bit rates allows more robust coding to be applied, and transmit power to be decreased, without decreasing BER performance. Note that the user data throughput is changing, but the on-air data rate remains constant, which is essential for LPE/LPD. Adaptive bit rate requires accurate LQA information, prioritization users, and prioritization of network requirements to be distributed throughout the network, just as with adaptive power. This data must be known, so that the trade off between throughput and robust coding (data rate) can be made automatically at each node. Specification and testing of bit rate control algorithms will be part of this study.

1.4.4.5 Time Randomization

The objective of time randomizations to make it extremely difficult to predict when the signal will be present. When coupled with frequency hopping, this implies pseudo random hop durations with arbitrary hop instants. The principal benefit of time randomization comes when detection is possible. In this case, time randomization prevents the interceptor from predicting when the signal will appear, which makes non-coherent integration (possibly for direction finding purposes) unlikely. Time randomization requires another level of synchronization (which may already be available if direct spreading is employed), but the most significant cost associated with time randomization is that the maximum duration of a single burst or hop is increased. This latter characteristic may increase the self-interference problem with multiple nets and certainly decrease the average hop rate, as minimum hop duration is fixed by training and delay spread constraints.

2.0 Approach

The approach taken to investigate, design, simulate and evaluate IHFDN followed the following sequence:

1. Establish a "point-of-departure" (POD), which integrated proven state-of-the-art techniques where applicable, and propose new techniques where required. The intent was to avoid "re-inventing the wheel", in areas where millions of man hours had already been expended by the technical community, and also to narrow the focus of the IHFDN effort to the areas of highest leverage.

2. Initiate "concept studies" which focus on several key areas of investigation, and impact IHFDN network design. The areas which were looked into were: HF channel modelling, bit error rate (BER) and HF channel parameter measurements during data reception and collision access method performance.

3. Develop a network simulation tool which implements the IHFDN techniques. This test platform can be used by developers to evaluate networking techniques, and by network designers to benchmark the performance of different network configurations.

4. Summarize the conclusions reached as a result of the concept studies and network simulations.

The remainder of section 2 deals with the first item in the above sequence, namely the point of departure. Each of the other steps in the approach (concept studies, network simulation, and conclusions) are covered in sections 3, 4, and 5 of this final report.

2.1 IHFDN Point of Departure

The Improved HF Data Network (IHFDN) is being designed using Harris knowledge and experience in the following key areas: HF communication, link quality analysis (LQA), frequency hopping (FH), low probability of detection and exploitation (LPD/LPE) modem waveforms, and HF networking techniques. The starting point for the IHFDN is called the "point of departure" or POD, and is a collection of existing techniques and ideas which serve as a foundation and a framework for the rest of the network design. Topics have been divided into the following areas, which loosely reflect the OSI layered approach.

Topic	Primary Issues
o Physical	Layer Topology, propagation, modulation, and channel parameters, frequency hopping, time sources
o Data Link Layer	Channel access, LQA
o Network Layer	Routing, congestion, error control, priority
o Transport Layer	Error control, flow control, connection management
o Higher Layers	Application, presentation, services to the operator

Table 2.1-1 OSI Layers and Issues

2.1.1 Physical Layer

The physical layer deals with the network topology, waveforms, and the HF channel.

The IHFDN topology will consist of nets of network users, each net having a common frequency hop set. The IHFDN can have up to 100 network members, divided into five to twenty nets. Each of the five nets could have no more than 20 members each, and each of the twenty nets

would have no more than five members each. The norm will be ten clusters of ten members each.

The preferred propagation modes within nets will be line of sight (LOS), beyond line of sight (BLOS) and near vertical incidence skywave (NVIS). All of these modes support propagation in the 0-400 mile range (for air to air communication), have similar propagation times (less than 4 ms), and have acceptable path loss within their range of propagation. Because a cluster can cover a geographic area no larger than can be supported by a common hop set, nets will be limited to areas with a diameter of approximately 400 miles. The cluster architecture will be discussed more in the Network Layer section.

Intercluster communication will primarily use 1 hop and multi-hop oblique skywave propagation. These modes are necessary to cover the long distance between nets (as much as 8000 miles), and network design will account for the associated large variation in propagation time (2-43 ms) and signal attenuation.

The HF modem used in the IHFDN must operate at data rates of 75 to 2400 bps in a 3 kHz bandwidth in a difficult HF channel: 5 ms multipath, 50 Hz Doppler, and 2 Hz fading bandwidth. The waveform which best meets these requirements is the serial tone, adaptive equalized waveform found in MIL-STD-188-110 CN2. Though this may not be the exact *waveform used in next generation HF networks* (due to future improvements), it is the closest match using today technology, and will be excellent for the IHFDN.

Adaptive equalization modems achieve high performance by their ability to learn and adapt to the HF channel parameters. This feature is an ideal integration of data waveform and link quality analysis in a single waveform. Besides saving time by performing both functions simultaneously, operational security (OPSEC) is improved, in that the two functions are indistinguishable on the air.

As part of the IHFDN program, MIL-STD-188-110 CN2 as implemented in the RF-5254B will be examined to determine the feasibility of extracting accurate channel measurements. SNR is currently the only channel parameter which is measured and displayed by the RF-5254B. Other parameters of interest are measured within the modem, but are not output for display or use in LQA. One activity in the IHFDN modem development will be the evaluation of the modems ability to measure and output the total channel character (the "impulse response"), made up primarily of SNR, multipath, and fading. Doppler offset is one channel characteristic which is available, but will not be output because all high performance modems internally correct for Doppler. Therefore it is not a parameter which affects BER performance.

Frequency hopping rates of 5 to 100 hps will be considered for the IHFDN. This range was

chosen due to the requirement to learn channel conditions on each hop (which takes time) and the need to hop at rates no faster than once per modem symbol. The 5-100 hps range covers hop rates currently used for passing frequency hopped high speed data over HF, and allows room for technological advancements. This range of hop rates exceeds the rates associated with the MIL-STD-188-110 CN2 modems under consideration (which has a symbol rate of 75 symbols/second). This waveform is unlikely to ever be hopped at greater than 15 hps due to dead time and time required to learn the channel. Though several hop rates may be used within the IHFDN, each will remain constant for long periods of time (i.e., no random rate frequency hopping will be used).

Each node in the IHFDN uses full duplex HF communication. In order to prevent colocation interference between the transmitter and receiver, isolation must be provided between the receiver and transmitter. This will be done by separating the transmit and receive frequencies. An alternative would be to use distance separation between the transmit and receive antennas, but this is not viable given the airborne platforms of the IHFDN. With current technology, a 10% separation between receive and transmit frequencies is a good rule of thumb. It is assumed that next generation technology will decrease this to 5%. It is interesting to know that if all usable frequencies have 5% separation, there are only 108 usable frequencies between 2 and 30 MHz. This reduces to 54 usable full duplex frequency pairs, or channels, which must be shared by several nets. 10% separation leads to 27 full duplex channels using the same line of reasoning. The bottom line of this analysis leads to the conclusion that the IHFDN must be efficient with frequency use and frequency hopping access methods must work with on the order of 10 to 20 frequencies.

All IHFDN nodes will have accurate local time sources with no more than 3 ms of error over a running time of 4 hours. This level of accuracy was drawn from the HAVE QUICK system specification, because it was thought that IHFDN nodes would have access to HAVE QUICK equipment and time standards. Note that even though HAVE QUICK is used in VHF and UHF frequency ranges, it does have several similarities with IHFDN waveform: predominantly used by USAF, frequency hopping, air to air communication, and ground to air communication.

2.1.2 Data Link Layer

The data link layer deals with link quality analysis and transmission of essentially error free data between any two network members (no relays).

Fast bit error rate measurements on a channel will be performed using a process based on the modem error correction coding. MIL-STD-188-141A, internal IR&D with the RF-3466 modem, and initial work with the RF-5254B have shown that this is a fast, accurate, and low overhead method for estimating BER. The primary benefit of this method is that it does not require

embedded test patterns or test probes which increase overhead, and reduce throughput.

LQA at the data link layer deals with the evaluation of channel conditions between the local node and any other node to which it can directly connect (no relay). The IHFDN study will assess the benefit -vs- cost of gathering LQA information.

Operational security, or OPSEC, will be maintained on point to point links by keeping on-air traffic level and modulation formats fairly constant. All forms of on-air traffic (LQA, data, voice) will have the same signature.

2.1.3 Network Layer

The network layer manages the routing and switching of information through intermediate nodes in the network.

The Network layer will utilize connectionless (CL) service. CL will be used for all forms of traffic, because it allows robust, adaptive routing in the presence of link and node outage.

Quality of service parameters will be furnished to the Network layer by the Transport layer: acceptable error and loss, message delay, throughput, priority, and LPE/LPD effectiveness. The Network layer will be flexible to allow optimization for any one of the quality parameters.

The network layer will be responsible for gathering and distributing data for use in the routing process. Capabilities include:

- Request, receive and transmit local routing table (all or part of)
- notify and be notified of damaged nodes or path redirection
- append and remove route history information within traffic
- note success/failure of routing attempts

Based on the destination of a message, each node will direct (or address) the message to the next node(s) in the path. The next node will be chosen using a least cost algorithm which takes the quality of service parameters into consideration. Messages may be sent along single paths, or redundantly along several paths. Messages may be addressed to nets, individuals, or ad-hoc groups of either.

Routing algorithms will be of the type generally referred to as "adaptive", in that decisions will be based on measurements and estimates of current real time traffic, topology and channel conditions. Both "isolated" and "distributed" adaptive routing techniques will used. The isolated methods make decisions based on information gathered only at the local node. They

are fairly simple, but do not deal with damage well. Distributed methods require nodes to share routing information, typically with adjacent neighbors, but sharing can also be global. Distributed techniques are best for handling node or path damage, but require the overhead of sharing routing information.

Routing algorithms will be evaluated on how well they satisfy the quality of service parameters. Algorithms can be described by the following attributes: correctness, simplicity, stability, fairness, optimality (well suited for actual conditions), efficiency (low overhead), and robustness (deal with loss or overload).

Multipath routing consists of sending messages or pieces of a message from source to destination along several different routes, rather than along the path which is clearly optimum. This technique will reduce congestion, and decreases vulnerability, but also means that less than optimum routes will be used at times.

Error control will be accomplished by reporting to the sender if packets are discarded or damaged. All datagram packets will be acknowledged on a point to point basis. Packets will have a lifetime, and will be discarded when the time expires. Both hop count and time to live methods for lifetime will be evaluated during our study.

Congestion control will be accomplished by squelching sources when a node becomes too congested. Appending and observing time stamps on packets (time in coming vs. time out going) will be used as a method of telling the time delay (congestion) within a given node.

The net topology described earlier in the physical layer is well suited for use in the IHFDN. A net is a group of individuals in a geographic area (400 mile diameter) with a need to intercommunicate. The common hop set used allows easy, quick internet communication, and propagation generally exists between all members. The network will be optimized for internet communication.

Addressing, relaying and LQA is simplified in that each individual only maintains information about individuals within his net, and information about the other nets as a whole (i.e., not every individual in every net). For example, given an IHFDN has 100 nodes, divided into 10 nets of 10 nodes each, each individual maintains data for 9 other intranet members and 9 other nets (9+9=18) rather than 99 other individuals. This greatly reduces overhead associated with LQA, and connectivity exchanges.

Intranet connections will typically be direct between the originator and final destination of the message. Internet connections can be made between any net individuals, not necessarily the source and destination nodes. Note that no individuals are assigned the sole responsibility of

being a "gateway" or "bridge" between nets. This was done to prevent bottlenecks, improve OPSEC, prevent single points of failures and make all nodes the same ("ordinary nodes"). Connections will rely on addressing of the form "net:individual". Once internet data arrives in the destination net, it is the responsibility of the net members to deliver it to the addressed individual.

In the interest of OPSEC, traffic (data and LQA activity) in the network will be maintained at equally distributed, relatively constant levels. This will be accomplished by controlling network loading and congestion.

Overhead in the data messages can be increased and decreased depending on loading. Optional overhead data includes: history of routing path, time stamps, and data used exclusively for BER evaluation.

2.1.4 Transport Layer

The purpose of the Transport layer is to provide end-to-end service between users.

The primary type of service will be CO, providing a logical connection between users. CL service will be used for the special cases of broadcast messages and routine (mail or memo type) messages which do not require connection.

Quality of service options specified by the user will be: acceptable error, acceptable message loss, message delay, throughput, priority, and LPE/LPD effectiveness.

Sequence control (duplicate detection) will be aided by each packet having an internal sequence number. The receiver will be prepared to deal with multiple images of packets. Packet sequence numbers will be used in the acknowledgment process.

Flow control will use credit allocations to acknowledge packets and ask for more. For example, A tells B that it has received X packets correctly, and is willing to receive Y more. A timer at the receive site will be used to retransmit acknowledgement and credit messages when the incoming data stops. Messages will be prevented from entering the network if the network is currently at full capacity, or running at a priority level higher than the incoming message.

Connection establishment will be made through a three way handshake which confirms a link is established. Source and destination addresses will be passed from the Transport layer to the Network layer. Connections will be managed to multiple ports at end users (voice and data to name two). Typically a two way handshake will be used to terminate a connection. In the absence of a proper handshake, a timeout will be used to terminate connections. A one way fast

abort disconnect will be allowed.

2.1.5 Higher Layers

The traffic destination and quality of service are specified by the user via the user interface. The lower layers use the desired quality of service to optimize the network accordingly: acceptable error and loss, message delay, throughput, and LPE/LPD effectiveness. The network will be flexible enough to allow optimization for any one of the quality options.

3.0 Concept Studies

Before it was possible to propose new networking techniques and implement them in a network simulator, it was necessary to investigate several "high leverage" areas:

- HF channel modelling
- bit error rate measurement during data transmissions
- multipath measurements during data transmissions
- throughput and delivery times for CSMA methods

The first area of investigation was the modelling of the HF channel. Though IONCAP is the de facto method of HF prediction in government and industry circles, it does not lend itself well to incorporation into a PC based, user friendly, fast execution network simulation tool. It was therefore necessary to come up with HF modelling techniques which were as accurate and fast as possible. Methods were investigated for the IHFDN which used both "HF handbook" methods and off line tabulated IONCAP results.

The IHFDN SOW requires that channel evaluation methods must be integrated with the data transmission methods, in order to minimize the on air time of all network users. One effective method for determining channel quality is to estimate the bit error rate (BER) during data transmissions, without the aid of time consuming bit test patterns. An accurate BER estimation technique was developed for IHFDN, and results are presented.

Another IHFDN requirement is the evaluation of HF channel characteristics in a way that does not require special sounding signals. Current MIL-STD-188-110 modems, such as the RF-5254C modem, already measure signal to noise ratio (SNR) during data transmission, so this is not an area requiring development. The HF parameter measurement which requires investigation is the measurement of is that of multipath arrivals. An accurate multipath measurement technique was developed for IHFDN, and results are presented.

Carrier sense multiple access (CSMA) is the most commonly used access methods for HF users. Either automatically, or manually, users transmit at will, and either detect collisions or not depending on the sophistication of the communication system. The HF channel suffers from the "hidden terminal" problem, in that transmitters may not always know whether a collision is in progress or not at the receive site, because receive conditions are different at the transmit and receive sites. Therefore simulations were conducted which evaluate the effect of different levels of collision detection effectiveness.

3.1 HF Modelling

The IHFDN techniques apply to networks which cover areas as large as an 8,000 mile diameter circle. It is of interest to analyze the range or extremes of HF propagation characteristics (frequency of operation, the path loss, SNR, propagation delays, etc.) which can be expected for this large area.

There are three methods of analyzing these parameters:

1. utilize existing HF Handbooks
2. utilize IONCAP predictions
3. perform on the air measurements

The IHFDN work concentrates on the first two methods and excludes the third as prohibitively expensive and time consuming (however there is no shortage of on-air measurement in technical literature). This report summarizes the process for the handbook method, and compares the results with those of IONCAP. The goal of this investigation is to decide which HF characteristics can be approximated through handbook calculation methods, and which must be approximated through IONCAP simulation.

3.1.1 Approach

Calculation of HF propagation characteristics utilizes a number of formulas and charts which can be found in a variety of HF references, the most widely referenced of which is CCIR Report 252 (reference 1). This and other references are listed in section 3.1.3, and are referenced throughout this section in the form of (reference, page), and should be consulted for more background on the HF calculations.

The handbook calculation approach is shown below:

1. Select earth surface distances ("great circle distances") for which calculation will be performed.
2. Select maximum and minimum virtual heights of the ionosphere.
3. Calculate take off angles and propagation path distances.
4. Select typical critical frequencies for vertical incidence, and calculate frequencies of transmission (FOTs) for the great circle distances.
5. Calculate propagation delay for each great circle distance.
6. Calculate and sum the various losses for the path.
7. Calculate receive SNR for each path.

To automate the calculation process listed above, and the related graphing, a Lotus 1-2-3 spread sheet was created which performs the calculations listed above. The first page of the spread sheet summarizes the input parameters as shown in table Prop 0. Tables (labelled Prop 1,2,3,4) and graphs from the spread sheet appear in this report.

The approach above shows that there is a great deal of work to estimate HF propagation characteristics. Propagation prediction programs such as IONCAP perform this type of analysis, plus much more, with much greater accuracy. In order to bench mark the handbook methods, IONCAP runs were made and the frequencies with the highest SNRs (i.e., the best frequencies) were examined. Throughout the rest of this report the characteristics of these best frequencies are compared with the calculated characteristics.

Table Prop 0:   Input Parameters

Input Parameters				Input Distances (miles)	
R = earth's radius	3960	miles		1	31.25
a = tx/rx platform height	6	miles		2	62.5
Hlow = low ionospheric layer hgt	62	miles		3	125
Hhi = high ionospheric layer hgt	311	miles		4	250
llow = low absorption index	0.1			5	500
lhi = high absorption index	1.7			6	750
Fh = gyro frequency	1.5	MHz		7	1000
Fvil = low virtual incidence freq	1.2	MHz		8	1500
Fvih = high virtual incidence freq	13	MHz		9	2000
Lg = loss per ground reflection	3	dB		10	3000
Ys = excess system loss	14	dB		11	4000
Stx = transmit signal power	30	dBw		12	6000
Gt = transmit antenna gain	0	dB		13	8000
Gr = Receive antenna gain	0	dB			

The following extreme conditions were used for the IONCAP runs. The end points of the links are listed in the following section.

Table 3.1.1-1 IONCAP Inputs

Month	Sun Spot Number	TX Power	RX Noise	Antenna Gain
July	10	1 KW	Suburban	O dB
January	10	1 KW	Suburban	O dB
July	110	1 KW	Suburban	O dB
January	110	1 KW	Suburban	O dB
July	190	1 KW	Suburban	O dB
January	190	1 KW	Suburban	O dB

3.1.1.1 Select Earth Distances

The IHFDN allows node separation of 0 to 8,000 miles. The methods used within this section 3.1.1 utilize the following library of distances in miles to cover the IHFDN range: 31.25, 62.5, 125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 miles.

Distances for the IONCAP simulation were based on the following sets of points. The first five sets are basically east-west and the remainder are basically north south.

Table 3.1.1-2 IONCAP Locations and Distance

New York City to Philadelphia	79 miles
New York City to Chicago	710 miles
New York City to Denver	1627 miles
New York City to Peking	6822 miles
New York City to San Francisco	2561 miles
New York City to Poughkeepsie	68 miles
New York City to Montreal	519 miles
New York City to Puerto Rico	1614 miles
New York City to Sucre, Bolivia	4164 miles
New York City to Puntas Areanas	6485 miles

3.1.1.2 Selection of Virtual Height

Virtual height of reflection is constrained by the minimum E layer height, and the maximum F2 layer height. The E layer is typically in the 90 to 130 km range (reference 1 page 73). For IHFDN calculations, 100 km, or 62 miles was selected as the minimum height. The F2 layer is typically between 225 and 500 km (reference 2, page 2-8). The maximum height for our calculations was 500 km, or 311 miles.

The output of IONCAP runs showed that virtual heights for the best frequencies of operation ranged from 102 km (63 miles) to 798 km (496 miles), though maximum heights of 550 km (342 miles) were the norm. The most extreme heights were from IONCAP runs in July.

Table 3.1.1-3 Virtual Heights

Height Extremes	IONCAP Extreme	Handbook Extreme
Minimum	102 km/63 mi	100 km/62 mi
Maximum	701 km/463 mi	500 km/311 mi

3.1.1.3 Take off Angle and Propagation Distance

Take off angle and propagation distance can be calculated using the great circle distance, the virtual height of reflection, tx/rx platform height, the number of hops, and relatively simple geometry. For IHFDN calculations, it was assumed that transmission and receive sites are airplanes at 31,680 feet, or 6 miles. Hops are assumed to be of equal length off the same layer. For example, a 2000 mile distance may be covered by two 1000 mile hops. The number of hops was determined to be the lowest number that would result in a take off angle greater than or equal to three degrees (the same as the IONCAP setting), and the frequency of transmission was less than 31 MHz (frequency calculations are in the next section).

Results are summarized in table Prop 1. Take off angles are plotted in figures 3.1.1.-1, 2 and 3, along with IONCAP comparisons. All these figures are for the same data, but the last two figures were expanded to show more resolution. The calculated and IONCAP results compare very well, typically differing by only a few degrees.

The equations are shown below for the take off angle (B) and propagation distance (L). As with

all the following tables, the "low" variable (example Llow) is calculated using the low virtual height. The "hi" variable (example Lhi) is calculated using the high virtual height. The take off angle equation can be found in reference 1 page 82 (the equation has been modified to account for differently defined variables, platforms above ground level, and for N hops). The L equation below can be derived geometry (see diagrams in reference 1, page 81).

$$B = \arctan [(\cos (d/2NR) - (R+a)/(R+H)) / \sin (d/2NR)]$$

$$L = 2N(\sin (d/2NR))(R+a)/\cos(d/2RN + B)$$

Where B = take off angle
    L = propagation distance through the atmosphere in miles
    R = earth radius (3960 miles assumed)
    a = height of platforms above earth (6 miles assumed)
    H = ionosphere virtual height (62 to 311 miles)
    d = great circle path length in miles
    d/NR = great circle arc of a hop in radians
    N = number of propagation hops

Table Prop 1: Takeoff Angle, Propagation Distance, FOT, and IONCAP Comparisons

Great Circle Dist. d miles	Hops at Hlow Nlow	Hops at Hhi Nhi	Takeoff Angle Degrees for Hlow Blow	Takeoff Angle Degrees for Hhi Bhi	Propagation (miles) Distance for Hlow Llow	Propagation (miles) Distance for Hhi Lhi	Freq.(MHz) of Transmission w/ Fvil & Hlow Flow	Freq.(MHz) of Transmission w/ Fvih & Hhi Fhi	IONCAP Dist. miles	IONCAP Takeoff Degrees Min.	IONCAP Takeoff Degrees Max.	FOT in MHz Min.	FOT in MHz Max.
31.25	1	1	74	87	116	611	1.2	12.2	68	63	83	2	13
62.5	1	1	60	84	129	613	1.3	12.2	79	59	82	2	13
125	1	1	41	78	169	624	1.7	12.4	518	12	47	3	17
250	1	1	23	66	276	663	2.7	13.1	709	7	39	5	23
500	1	1	11	48	516	801	4.5	15.6	1614	4	26	8	30
750	1	1	6	35	764	990	5.8	18.6	1627	3	15	8	30
1000	1	1	3	27	1014	1205	6.5	21.7	2561	4	20	6	30
1500	2	1	6	16	1529	1672	5.8	27.0	4164	3	14	6	30
2000	2	1	3	9	2028	2161	6.5	30.5	6485	3	18	6	30
3000	3	2	3	16	3042	3344	6.5	27.0	6823	3	16	8	23
4000	4	2	3	9	4056	4322	6.5	30.5					
6000	6	3	3	9	6085	6483	6.5	30.5					
8000	8	4	3	9	8113	8644	6.5	30.5					
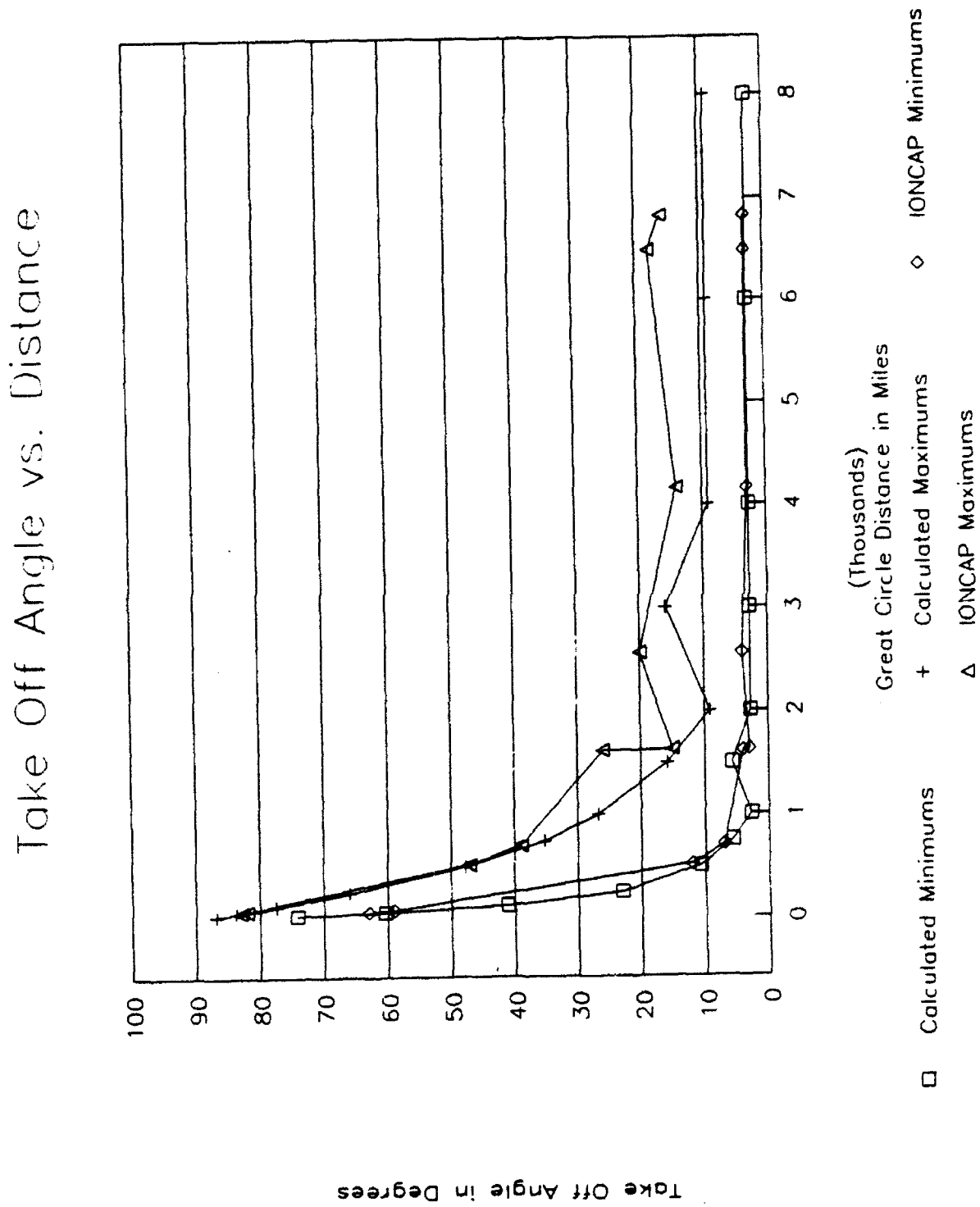
Figure 3.1.1-1

Take Off Angle vs. Distance
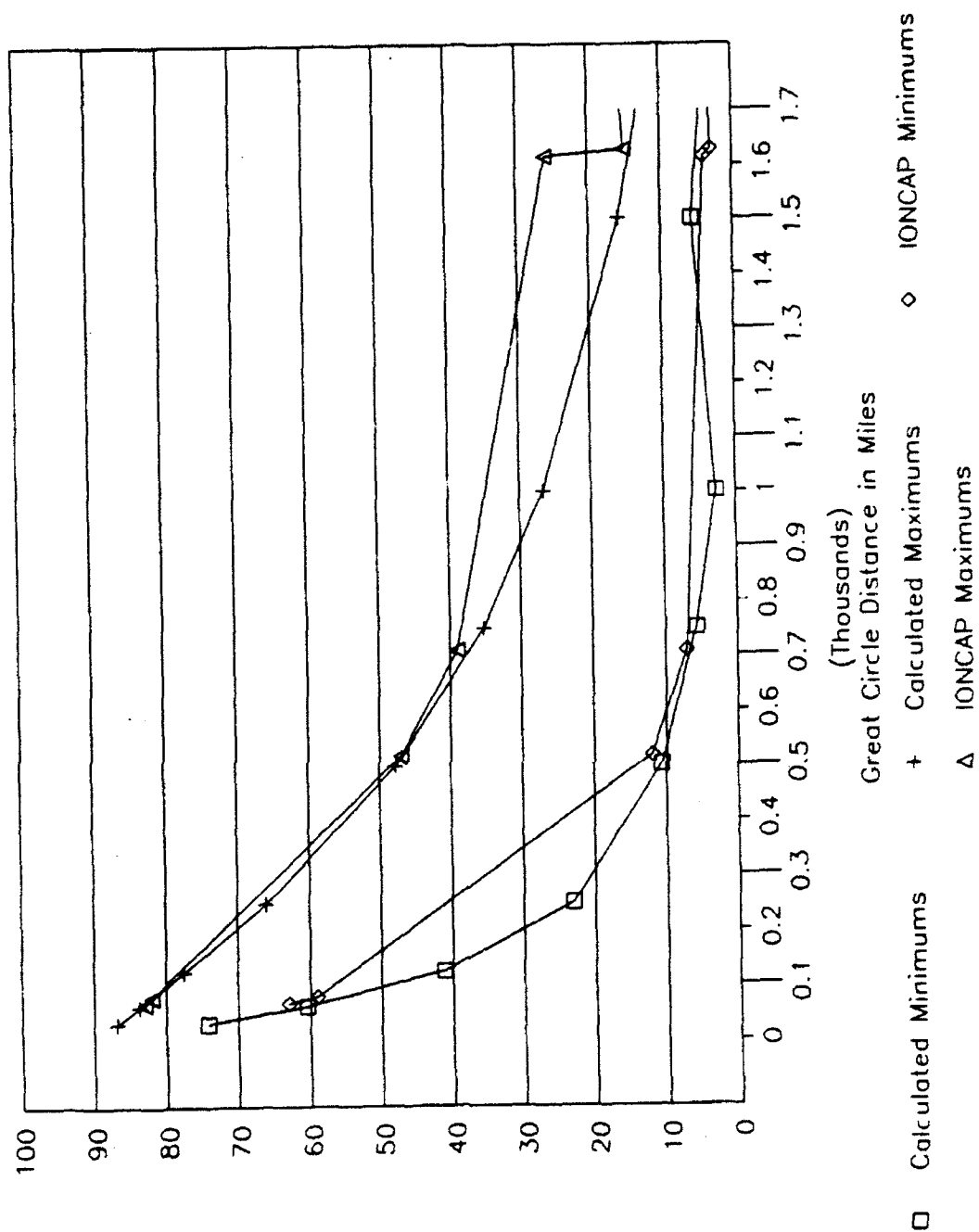
Figure 3.1.1-2

Take Off Angle vs. Distance

(Thousands)
Great Circle Distance in Miles

□   Calculated Minimums   +   Calculated Maximums   ◇   IONCAP Minimums

△   IONCAP Maximums
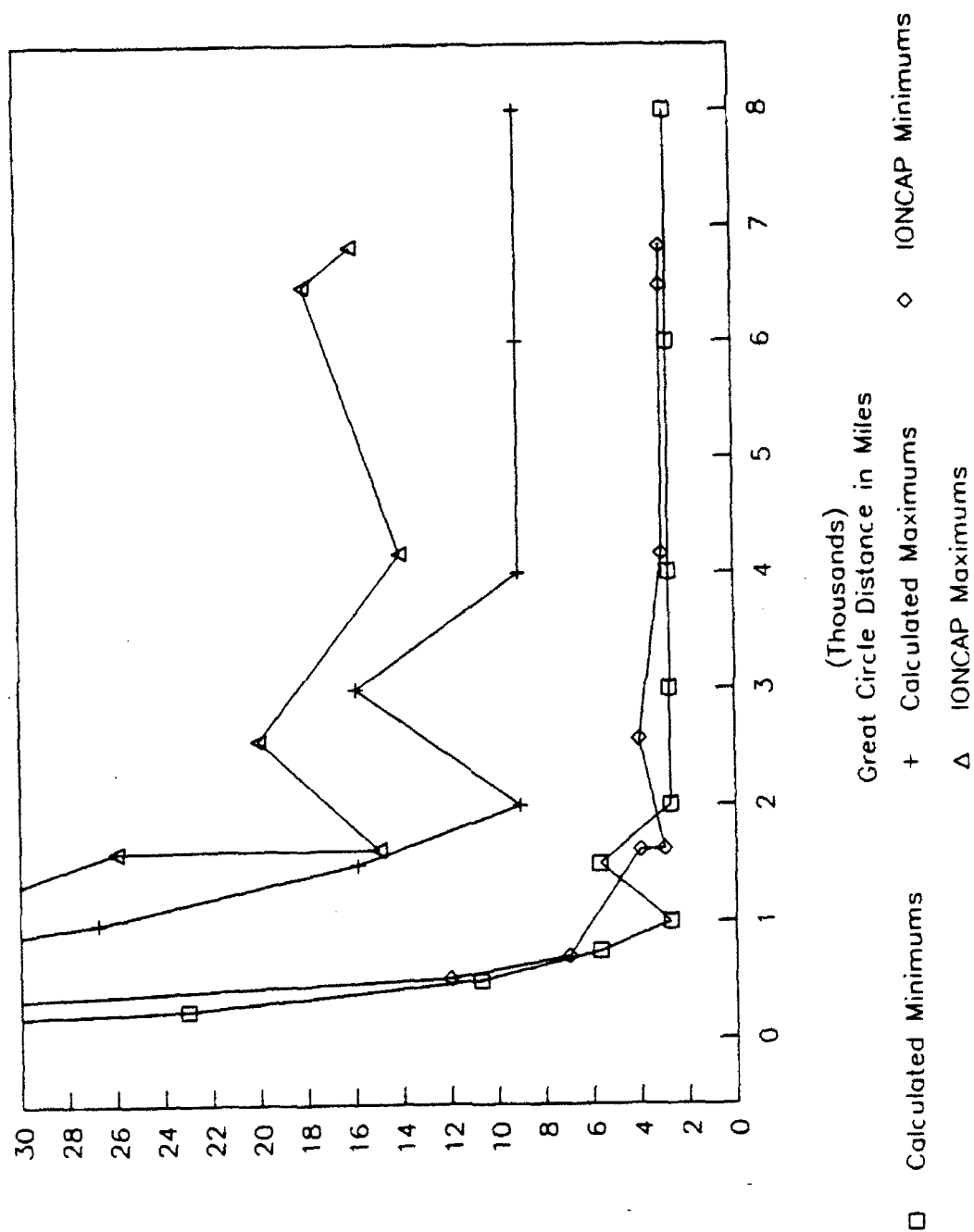
Figure 3.1.1-3

3.1.1.4 Selection of Typical FOTs

The optimum working frequency (FOT) was assumed to be 85% of the maximum usable frequency (MUF):

FOT = .85 (MUF) (reference 2 page 2-11)

The MUF was calculated by applying the secant law to assumed vertical incidence critical frequencies:

MUF = fo * k * sec (phi) (reference 1 page 79)

fo is the critical frequency for the layer; assumed to be 1.2 MHz for the E layer (reference 2, page 2-8) and 13 MHz for the F2 layer. (reference 3, page 23)

where k is a correction factor for the curved geometry (a number in the range of 1.0 to 1.2, and assumed to be 1.1 in our calculations (reference 2 page 2-10).

sec (phi) = 1/sqrt[(1-((R+a) (cos B)/(R+h))^2)] from geometry.

Therefore, substituting MUF into the FOT equation yields:

FOT = (.935*fo)/ sqrt((1-((R+a)(cosB)/R+H))^2)

where:
R = radius of the earth
a = height of platforms
B = take off angle
H = virtual height
fo = layer critical frequency

Figures 3.1.1-4,5 compare the FOTs calculated for low and high virtual heights with the IONCAP minimum and maximum values. Again, the calculated and IONCAP values compare well.
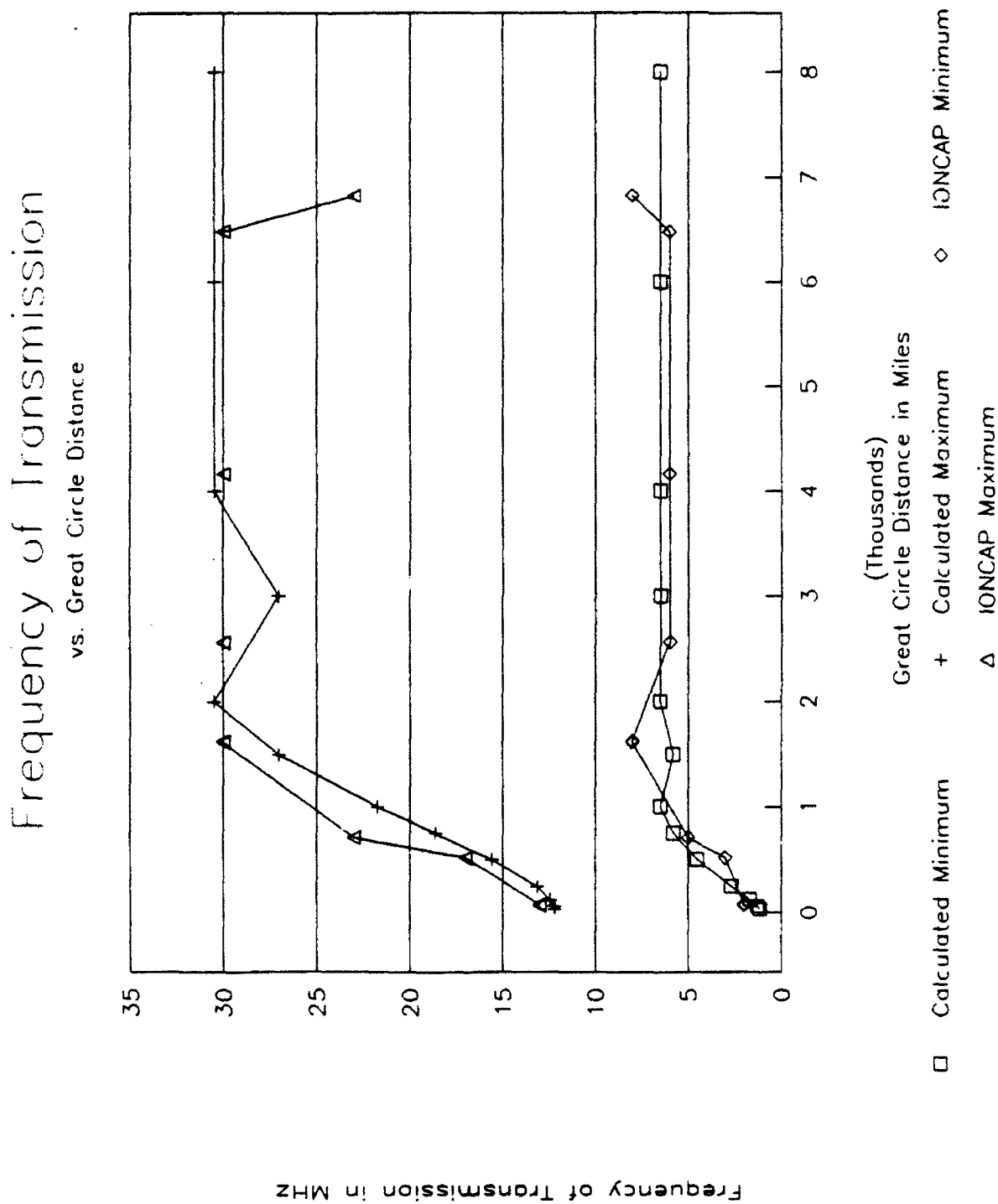
Figure 3.1.1-4
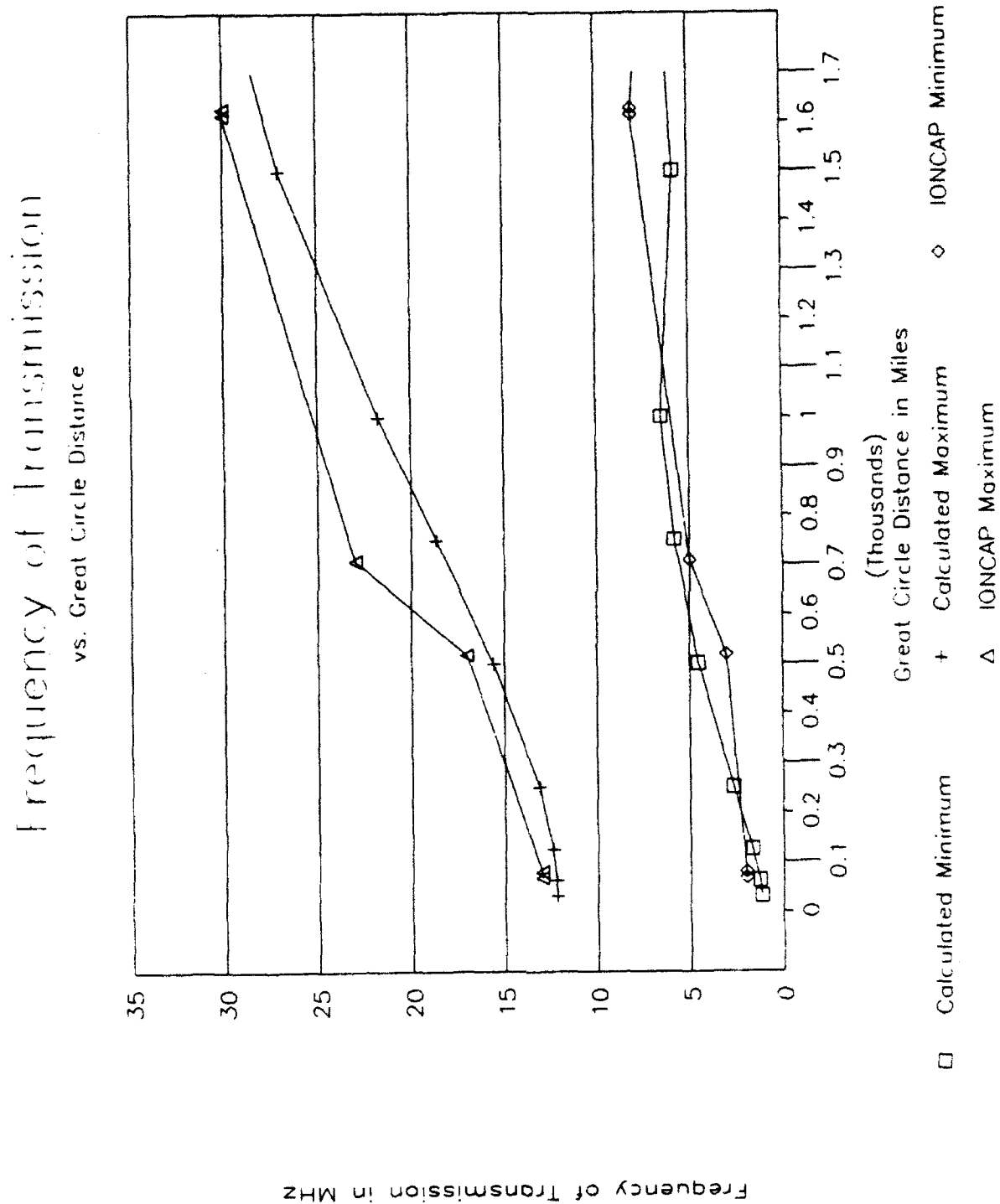
Figure 3.1.1-5

3.1.1.5 Propagation Delay

Estimation of propagation delay is based on the speed of the propagating wave and the distance it has to travel:

$$T = L/186.45$$

where T = delay in msec
   L = propagation distance in miles (from table Prop 1)
   186.45 = speed of light in miles/msec

Figures 3.1.1-6,7 compare the calculated propagation delays with the delays from the best SNR IONCAP channels. The calculated and IONCAP values are typically within half of a millisecond of each other, with the exception of two very abnormal points at 256 and 4164 miles. If these unique points are replaced with the values from the next bast frequencies, figures 3.1.1-8 and 3.1.1-9 result.

Table Prop 2: Propagation Delay and IONCAP Comparisons

| Great Circle Dist. d miles | Propagation Delay for | | Multipath Delay (delta) M msec | IONCAP Delay | | IONCAP Delay Modified | |
	Hlow Tlow msec	Hhi Thi msec		Min. msec	Max. msec	Min. msec	Max. msec
31.25	0.6	3.3	2.65				
62.5	0.7	3.3	2.60				
125	0.9	3.3	2.44				
250	1.5	3.6	2.08				
500	2.8	4.3	1.53				
750	4.1	5.3	1.21				
1000	5.4	6.5	1.02				
1500	8.2	9.0	0.77				
2000	10.9	11.6	0.71				
3000	16.3	17.9	1.62				
4000	21.8	23.2	1.42				
6000	32.6	34.8	2.14				
8000	43.5	46.4	2.85				
68				0.8	3.3	0.8	3.3
79				0.8	3.3	0.8	3.3
518				2.9	4.4	2.9	4.4
709				3.9	5.3	3.9	5.3
1614				8.9	10.2	8.9	10.2
1627				9	9.7	9	9.7
2561				14	22.3	14	15.7
4164				22.9	37.3	22.9	23.9
6485				36.1	39.3	36.1	39.3
6823				38.2	40	38.2	40

Propagation Delay vs. Distance

Figure 3.1.1-6

Figure 3.1.1-7

Propagation Delay vs. Distance

(Thousands)
Great Circle Distance in Miles

□ Calculated Minimums   + Calculated Maximums   ◇ IONCAP Minimums

                          △ IONCAP Maximums
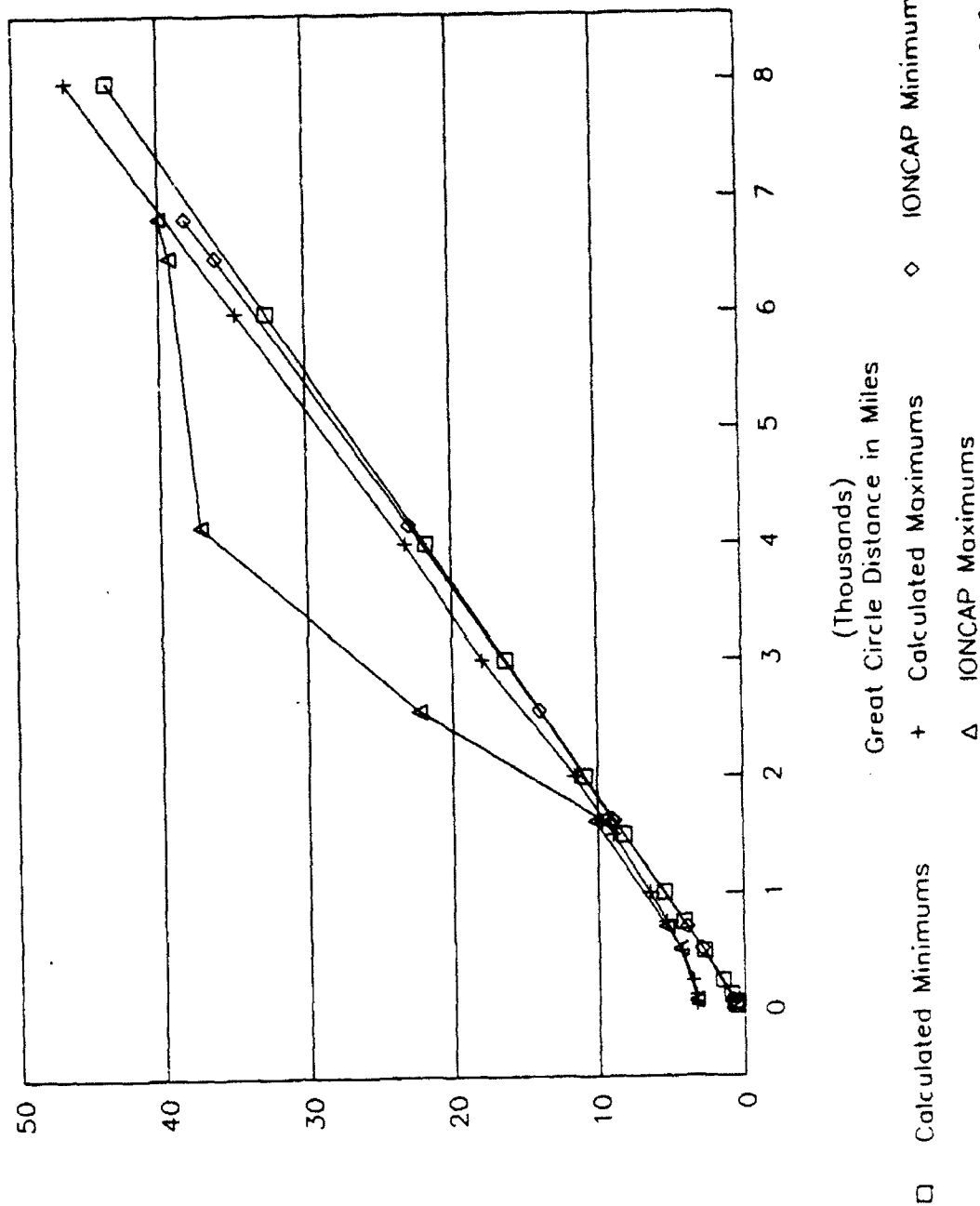
Propagation Delay in msec
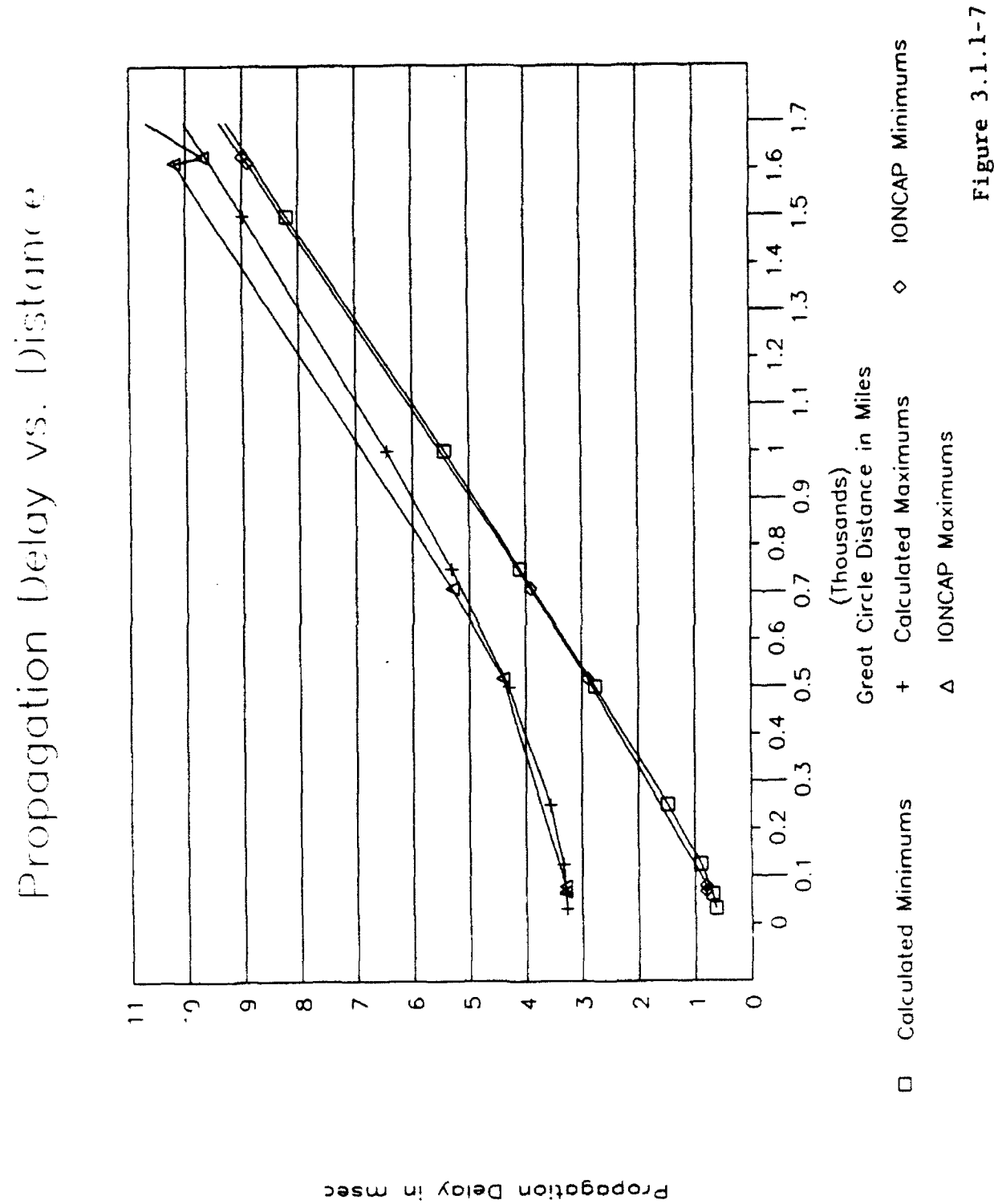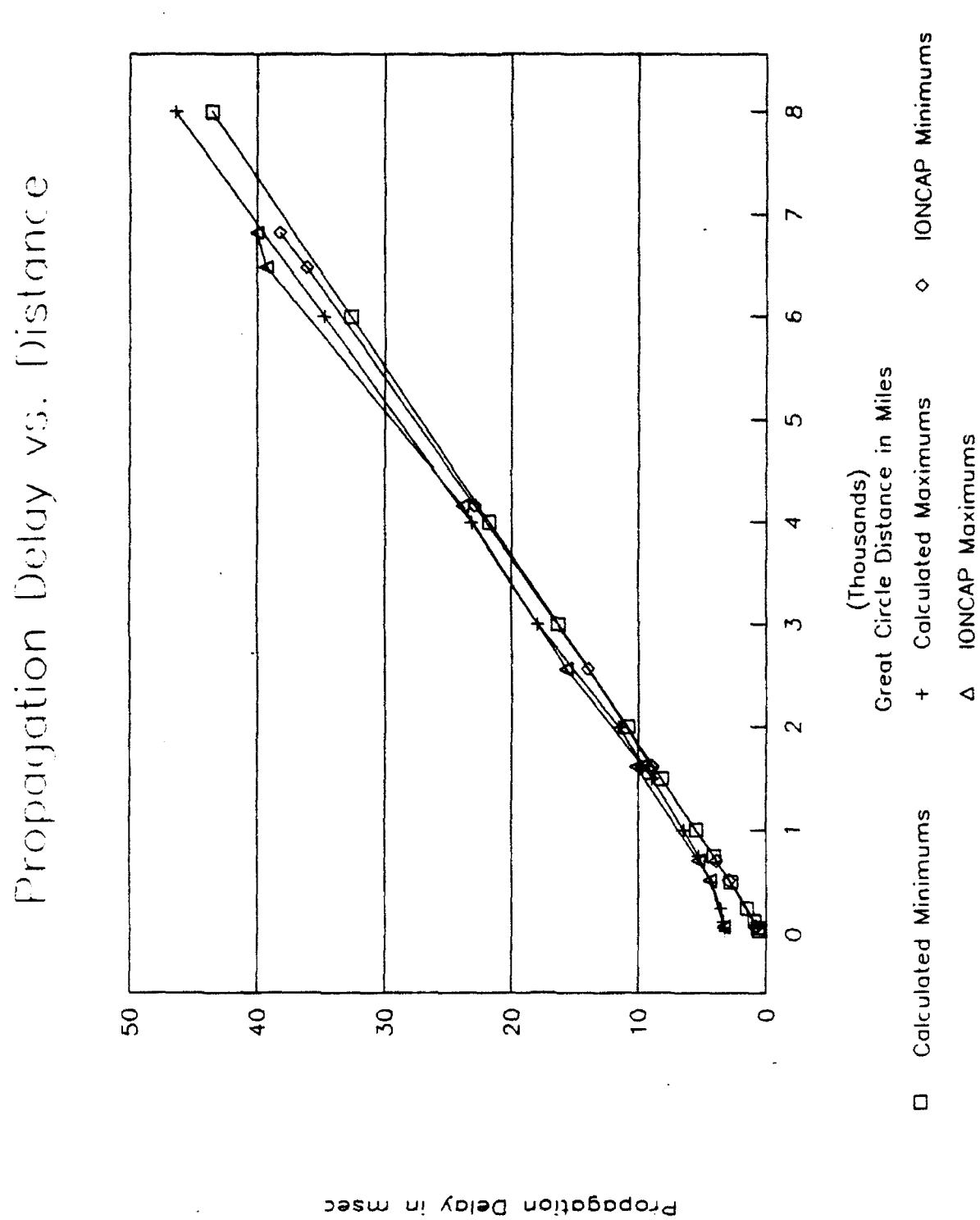
Figure 3.1.1-8

Propagation Delay vs. Distance

Great Circle Distance in Miles
(Thousands)

□　Calculated Minimums　　　+　Calculated Maximums

◇　IONCAP Minimums　　　　△　IONCAP Maximums

Propagation Delay in msec
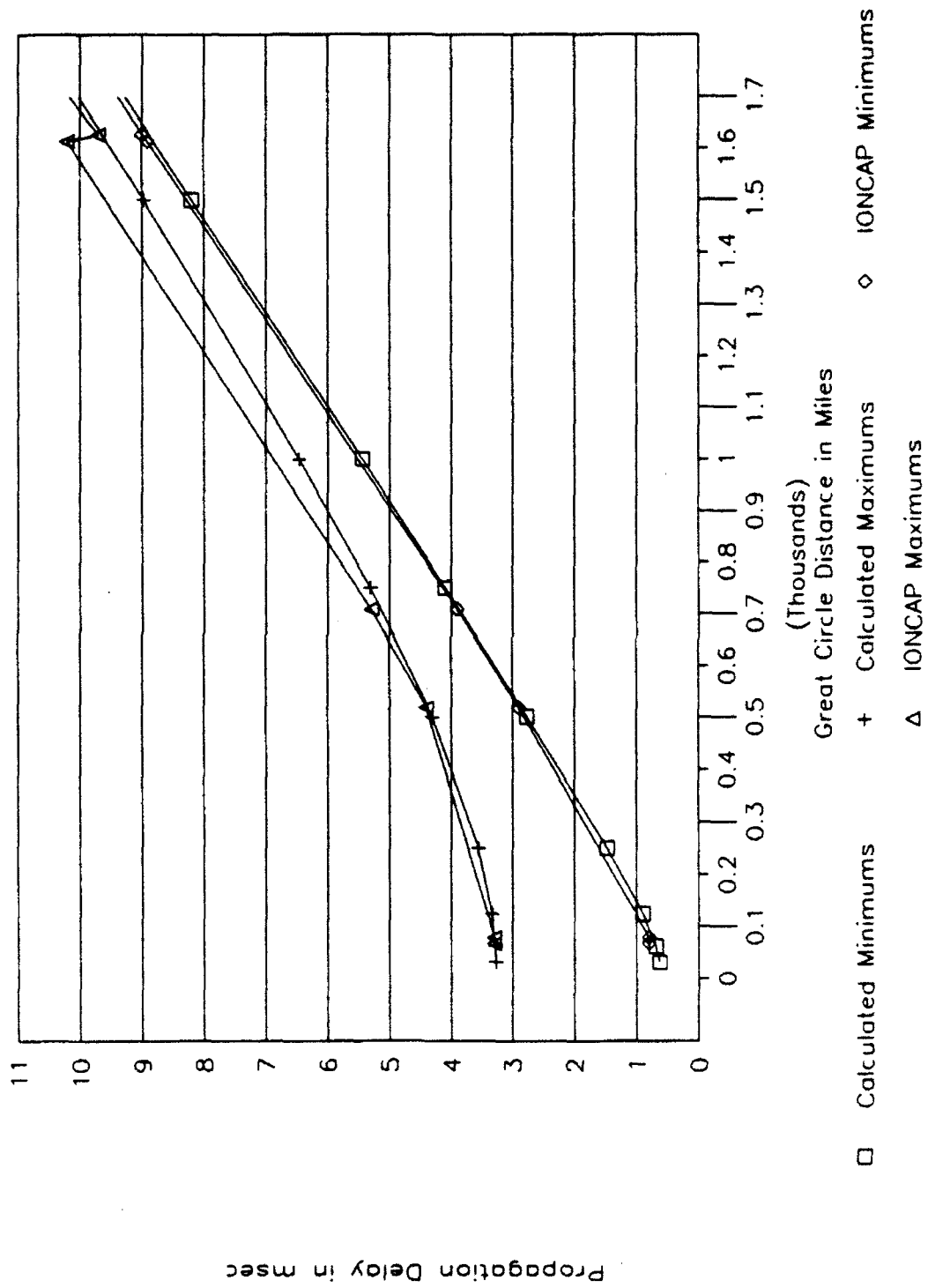
Figure 3.1.1-9

3.1.1.6 Loss Calculation

System loss, Ls, can be estimated from the summation:

Ls = Lbf + Li + Lg + Yp - (Gt + Gr)   (reference 1, page 99)

Where:
Li = ionospheric absorption loss in dB
Lbf = free space loss in dB
Lg = ground reflection loss in dB
Yp = Excess system loss in dB
Gt, Gr = transmit and receive antenna gains (dB) relative to isotropic

Absorption loss, Li, as the name implies, is due to absorption by the ionosphere, and is dependent upon the geographic location, the gyro frequency, sun spots, and absorption index. Li was calculated using:

$$Li = \frac{677.2 \, I \, N}{((F + Fh)^{1.98} + 10.2) \cos (phi)}$$ (reference 1 page 92)

where:
I = Absorption index (assume range of 0.1 (reference 1 page 93) to 1.7 (reference 2 page 2-32))
N = Number of hops
F = Operating frequency in MHz (low and high FOTs; table Prop 1)
Fh = Gyro Frequency in MHz (use 1.5 MHz) (reference 2 page 2-31)
phi = angle of incidence at 100 km level
cos(phi) = square root [1 - ((R + a)(cos B)/(R + 62.2))^2] from geometry

where R = earth radius in miles
a = platform height in miles
B = take off angle

The basic transmission loss in free space, Lbf, is due to natural spreading out of the transmitted wave as in travels through the media. It can be found from nomograms or from the equation below (reference 1, page 91 converted to miles).

$$Lbf = 36.57 + 20 \log F + 20 \operatorname{Log} L$$

Where   Lbf is the free space loss in dB.
   F is the frequency in MHz (from table Prop 1)
   L is the propagation distance in miles (from table Prop 1)

Absorption loss at ground reflections is typically 0.5 to 4 dB per reflection for take off angles less than 10 degrees (most multihop modes in table Prop 1 have take off angles less than 10 degrees). For the purpose of the IHFDN calculations, 3 dB per ground reflection is assumed (reference 2 page 2-27, 2-28).

Excess system loss is a "fudge factor" which is applied to calculated loss values to account for losses not explicitly attributed for the losses described above. It is dependent on time of day, latitude, and month, and varies from 9 to 19 dB (reference 1 pages 94 through 97). For the IHFDN calculations, it is assumed to be 14 dB.

Table Prop 3 summarizes the loss numbers for the propagation paths. The data is plotted in figures 3.1.1-10, 11, 12. If all of the above losses are summed, then the calculated and IONCAP maximum loss predictions agree to the about 10 dB (figure 3.1.1-10, 11). To make the calculated values compare with the minimum IONCAP results, it is necessary to neglect absorption and excess system losses (figure 3.1.1-12).

It is clear that the range of calculated loss is great, depending on the HF condition. This reinforces the need for prediction program like IONCAP which use much more complex and accurate methods than those used above, if the user is trying to predict the loss for a specific sunspot number and time of year.

Table Prop 3: Losses and IONCAP Comparisons

Great Circle Distance	Gnd Loss (dB)		Free Space Loss (dB)		Absorption Loss (dB)		Total Loss (dB) Lbf+Lr+Li+Ls-G		IONCAP	East West Loss (dB)		North South Loss (dB)	
d miles	low	high	low	high	low	high	low	high	d				
	Lglow	Lghi	Lbflow	Lbfhi	Lilow	Lihi	Lslow	Lshi	miles				
31.25	0	0	79	114	4	6	97	134	79	96	130		
62.5	0	0	81	114	4	6	99	134	710	112	139		
125	0	0	86	114	5	6	105	134	1627	126	145		
250	0	0	94	115	6	6	114	135	2561	133	178		
500	0	0	104	118	6	5	124	138	6822	157	192		
750	0	0	110	122	6	5	129	141	68			96	131
1000	0	0	113	125	5	5	132	144	518			108	135
1500	3	0	116	130	11	5	144	148	1614			129	157
2000	3	0	119	133	11	5	147	152	4164			144	187
3000	6	3	122	136	16	9	159	162	6485			147	183
4000	9	3	125	139	22	10	170	166					
6000	15	6	129	142	33	16	190	178					
8000	21	9	131	145	44	21	210	189					

Propagation Loss
vs. Great Circle Distance

Propagation Loss in dB

(Thousands)
Great Circle Distance in Miles

☐ Calc. Low Freqs   + Calc. High Freqs   ◇ IONCAP E–W Minimum

△ IONCAP E–W Maximum   × IONCAP N–S Minimum   ▽ IONCAP N–S Maximum

Figure 3.1.1-10

Figure 3.1.1-11

Propagation Loss
(Neglecting Absorption and Excess Loss)
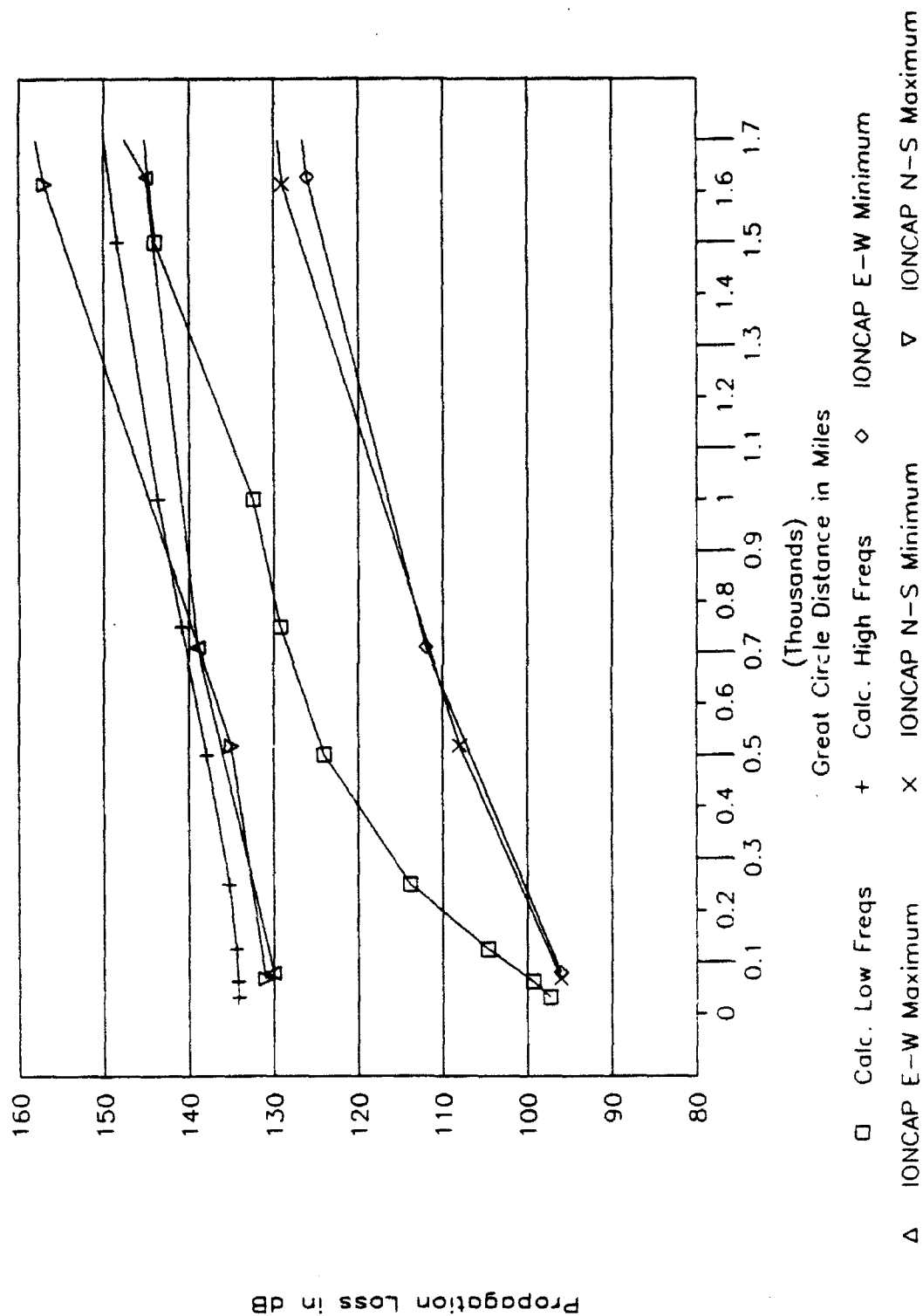
Figure 3.1.1-12
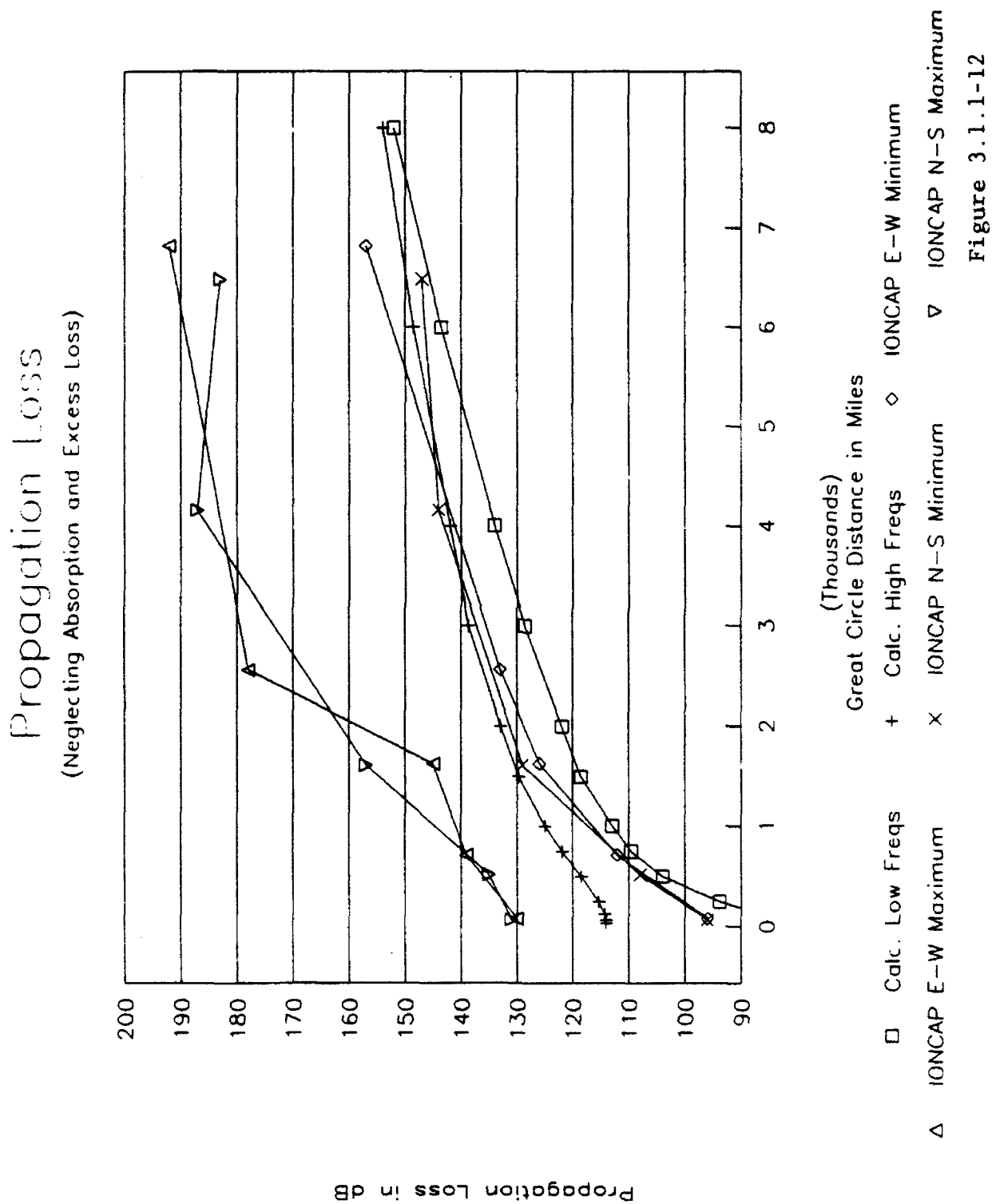
3.1.1.7 SNR Calculation

SNR at the receive site is calculated using the formula below, which assume a net antenna gain of 0 dB at the transmit and receive sites.

$$SNR = Stx - Nrx$$
$$SNR = (Stx - Ls) - Nrx$$
$$SNR = Srx - Nrx$$

Where:

SNR = the signal-to-noise ratio in dB (3 kHz noise bandwidth)
Stx = the transmit signal level in dBW; here, 30 dBW for 1kW.
Ls = Total system loss from table Prop 3 in dB.
Srx = the signal level at the receive site dBw
Nrx = noise level at receive site (dBW)
  = -27.6 log F MHz - 122.3 (IONCAP suburban 1 Hz noise BW)
  = -27.6 log F MHz - 87.5 (IONCAP suburban 3 kHz noise BW)

Results are summarized in table Prop 4, and plotted in figures 3.1.1-13, 14, 15. Figure 3.1.1-13, 14 use loss values from figure 3.1.1-10, 11 and shows good comparison with IONCAP minimum SNRs. Figure 3.1.1-15 uses loss values from figure 3.1.1-12 (neglecting excess system loss and absorption loss) and compares well with maximum IONCAP SNR values.

Table Prop 4: SNR and IONCAP Comparisons

Great Circle Distance	RX Signal		RX 3KHz Noise		RX 3KHz SNR		Dist.	IONCAP			
	Low	High	Low	High	Low	High		East West SNR		North South SNR	
	Srxlow	Srxhi	Nrxlow	Nrxhi	SNRlow	SNRhi		Min.	Max.	Min.	Max.
d miles	dBW	dBW	dBW	dBW	dB	dB	miles	dB	dB	dB	dB
31.25	-67	-104	-89	-117	22	13	79	12	35		
62.5	-69	-104	-91	-118	21	13	710	12	31		
125	-75	-104	-94	-118	19	13	1627	5	23		
250	-84	-105	-99	-118	15	13	2561	-39	13		
500	-94	-108	-106	-120	12	13	6822	-44	-5		
750	-99	-111	-109	-123	9	12	68			12	36
1000	-102	-114	-110	-124	8	11	518			14	32
1500	-114	-118	-109	-127	-5	9	1614			-6	19
2000	-117	-122	-110	-128	-7	6	4164			-35	9
3000	-129	-132	-110	-127	-19	5	6485			-27	5
4000	-140	-136	-110	-128	-30	-8					
6000	-160	-148	-110	-128	-50	-20					
8000	-180	-159	-110	-128	-70	-31					

Receive SNR (3kHz Noise BW)
vs. Great Circle Distance

3 kHz SNR in dB

(Thousands)
Great Circle Distance in Miles

□ Calc. Low Freqs   + Calc. High Freqs   ◇ IONCAP E-W Minimum
△ IONCAP E-W Maximum   × IONCAP N-S Minimum   ▽ IONCAP N-S Maximum

Figure 3.1.1-13

Figure 3.1.1-14

Figure 3.1.1-15

3.1.2 Calculations Conclusions

The goal of the numerical methods explored above, was to explore the validity of simple HF parameter calculations, when compared to IONCAP results. This goal was met, in that a straight forward spread sheet was created which allows the user to manipulate HF conditions (critical frequencies, link end points, minimum take off angles,etc.). Numerical results are seen in a fraction of a second, and graphical results can be seen three key strokes later. Despite its simplicity, the validity of the approach was confirmed with comparisons to IONCAP data, which showed vary similar results. For situation which requires the determination of HF propagation boundary conditions, this approach should be considered.

3.1.3 References for Section 3.1

1. CCIR Report 252-2. CCIR Interim Method for Estimating Sky-Wave Field Strength and Transmission Loss at Frequencies Between the Approximate Limits of 2 and 30 MHz. 1970.

2. H-F Antenna Selection. Engineering Compendium. Collins Radio Company.

3. Planning and Engineering of Shortwave Links. Gerhard Braum. 1982.

3.2 Bit Error Rate (BER) Measurements

Measuring BER during normal user data transmissions (i.e. not using lengthy, known test patterns) is extremely time efficient, and results in operational security (OPSEC) in that there is no differentiation between data, voice, LQA, and network initialization. This directly addresses the LPD/LPE objective of this study. The BER estimation method tested for this study uses the normal MIL-STD 188-110A modem convolution decoder (rates 1/2 convolutional code of constraint length 7). The decoder uses a trellis trace back process to produce corrected information bits, which implies corrected encoded bits. By comparing the received encoded bits with the corrected encoded bits, errors can be counted. Figure 3.2-1 shows the accurate relationship between the predicted and actual error rates. Each data point represents and average of 1000 observation periods of 150 msec each (2 1/2 minutes if run continuously). the 150 msec periods were chosen to accommodate slow frequency hopping.
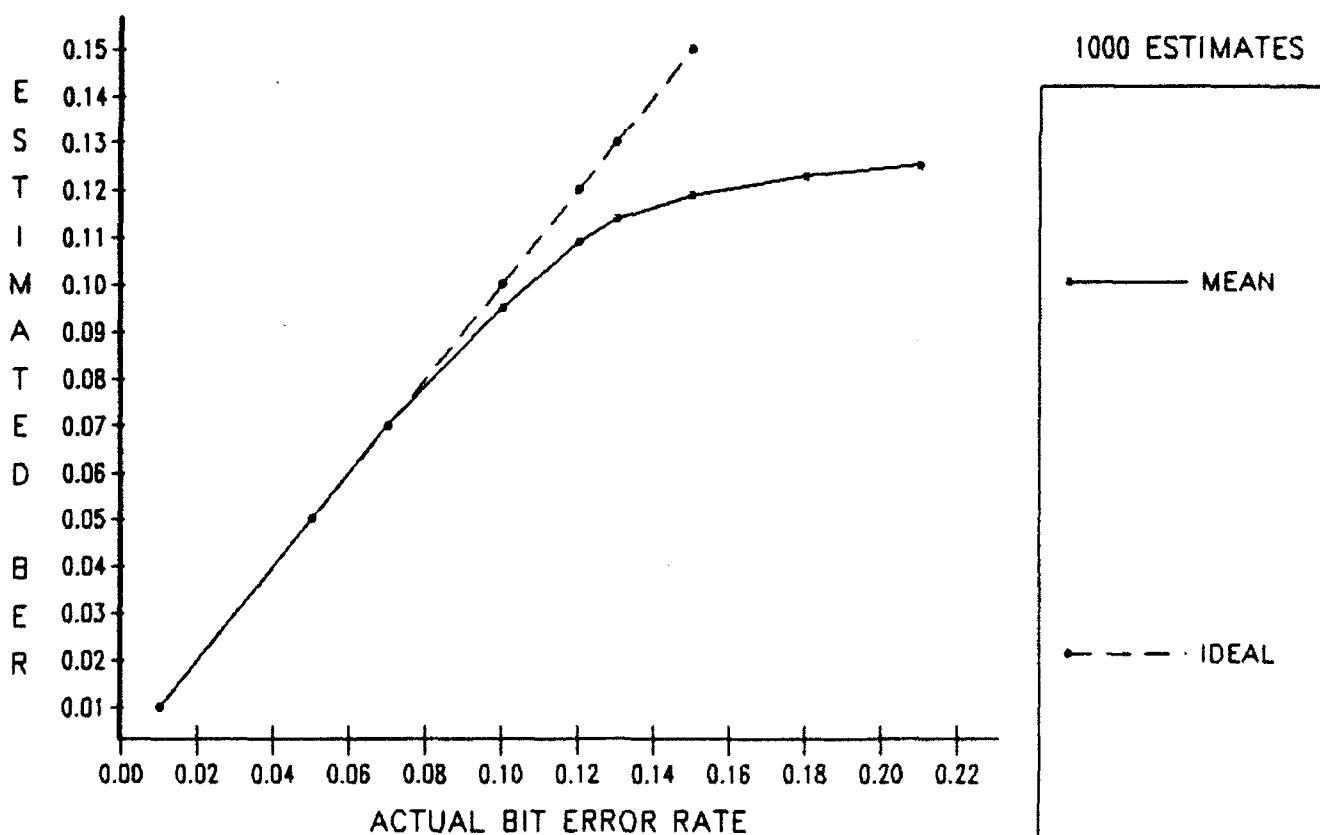
Figure 3.2-1

3.3 Channel Evaluation

Receive processing with the MIL-STD-188-110A modem allows access to all important channel evaluation parameters. The impulse response of the HF channel is an indicator of multipath and fading, and is easily extracted from the complex channel weights of a channel equalizer. Figure 3.3-1 shows simulated MIL-STD-188-110A modem equalizer tap weights, directly implying the channel impulse response. This channel had 2 msec multipath, 2 Hz fading, and a SNDR = 43 dB (8 dB SNR in 3KHz bandwidth). The multipath spread measurement is made from this data by doubling the rms spread (or standard deviation, sigma) of the distribution shown.

Frequency offset and SNR can also be extracted from a MIL-STD-188-110 modem. By removing frequency offsets in the receive signal, modem Doppler correction processes provide a measure of Doppler offset. To make SNR measurements, received m-ary PSK phase vectors are compared with ideal phase vectors after removing all channel perturbations (multipath, fading, and Doppler). Commercially available modems (example Harris RF-5254C) currently display receive SNR on the front panel, so this is not an area requiring additional investigation.
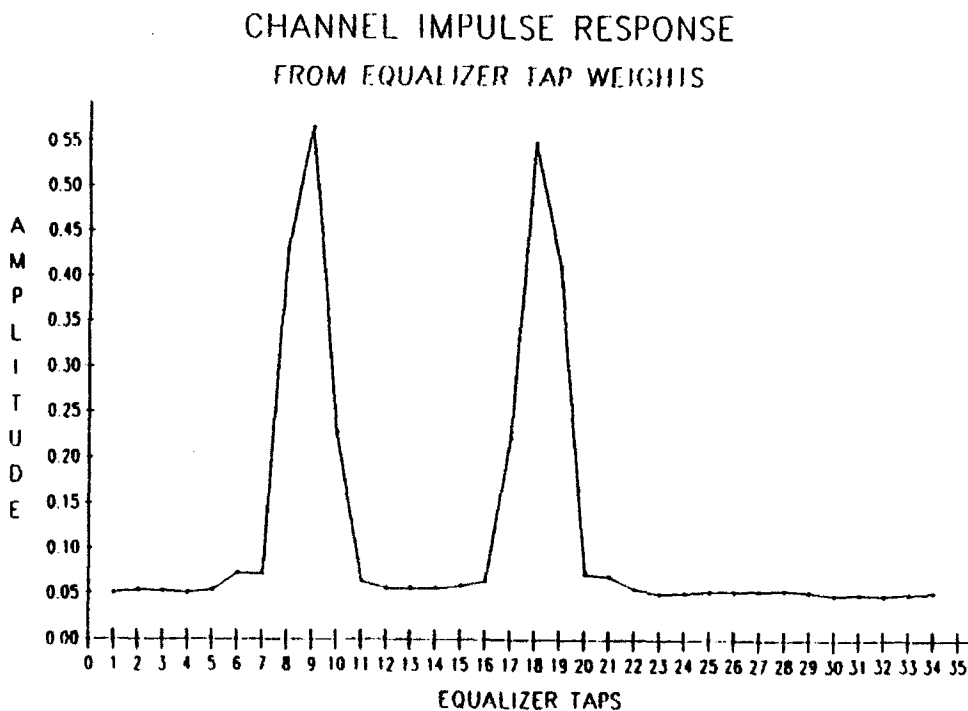
Figure 3.3-1

3.4 CSMA Access Method Simulation

This study was undertaken to better understand the performance of CSMA link access techniques in an HF environment.

Goals:

1   Study CSMA link access methods using a packet level simulation.

2)   Use a pac .et size reasonable for the hopping HF environment.

3)   Study the effect of message density, maximum reschedule interval, and collision avoidance performance on message delivery time.

4)   Better understand the performance of a PC for low level simulation.

5)   Provide a baseline for comparison of other access methods.

Expected Results:

1)   Plot a family of curves of normalized message delay versus message density for collision avoidance performance of 0-100 percent and maximum reschedule intervals of 10-40 times the packet length.

2)   Overall impressions of PC performance as a simulation engine.

Tools:

1)   Wyse 12.5 MHz PC AT

2)   Microsoft C5.0 and quick C

3)   Microsoft EXCEL spreadsheet for plotting results

4)   Digital LN03R postscript laser printer for graphics output

Assumptions and Limitations:

1)   The only source of packet errors considered are packet collisions.

2)   Any undetected overlap of packets in time is considered a collision, resulting in a bad packet.

3)   Messages are scheduled randomly over 24 one hour periods using a uniform distribution.

4)   Each message is assumed to have access to the link when it needs to send. The is no message queuing in the model.

5)   Array sizes limit the present program to about 150 messages per hour.

6)   Each message is assumed to contain five packets. Each packet has the following format, for the total length of four seconds:

  - 200 msec preamble (transmitting end)
  - 5 600 msec modem super blocks (transmitting end)
  - 1 200 msec preamble (response block from receiving end)
  - 1 600 msec modem super block (response block from receiving end)

SIMULATION OVERVIEW:

Initialization:

The simulation starts by initializing an array structure for a twenty four hour period. The random number generator is used to generate a number between 0 and 3599 as a start time in seconds for a message and also a number between 0 and 999 as the start time in milliseconds. These two numbers are added and become the message start time. This process is repeated N times where N is the message density in messages per hour. Finally this process is repeated 24 times to fill the arrays for the 24 hour period. These arrays also contain on a message basis the variables: packet start time, message send time, packets in message, and packets remaining to be sent. For purposes of this simulation each message was initialized to contain five packets.

Main Processing:

The main processing loop scans the array of packet start times and finds the earliest. The next earliest packet is found and its start time is compared to the earlier packet's end time to see if an overlap occurred.

> If no overlap occurred then there was no collision, and the number of remaining packets remaining is decremented.

>> If the remaining packets are zero, the message is declared sent, the messages sent counter is updated, the message end time is entered into the array and the packet start time is set to a done state.

> If an overlap occurred, decide if the second transmitter detected the presence of the first transmitter. This is done using the random number generator and the collision avoidance performance percentage.

>> If it was decided that the first transmitter was detected, and therefore the collision was avoided, the second packet is rescheduled to start (try again) 50 msec after the end of the first packet. At this time, we must iterate the collision occurred loop to handle more than two packets colliding at once.

>> If it was decided that the collision really occurred, the collision counter is updated and the first packet is rescheduled using the random number generator to return a number between 0 and the maximum reschedule interval. This is added to the end time of the first packet and becomes its new start time. Next it must be determined if the second packet collided with any other packets.

>>> If there were no additional collisions, the second packet is rescheduled as above and the main loop executed again.

>>> If additional collisions are detected, the collision occurred loop is reentered with the second and third packets continuing the process until no new collisions are found.

The above processing continues until all packets are sent. This was then iterated four times to average (or smooth) out the results.

Final Processing

The results are printed including average message delivery time, standard deviation of the message delivery tim, packets sent, packet collisions, and messages sent.

The above data was entered into EXCEL and the results normalized. The average message delivery time is divided by the message length (20 seconds) to produce "Normalized Message Delivery Time". The input messages per hour are divided by the maximum messages per hour (180) to produce "Message Density". From this data the family of curves that follows were plotted:

Results:

It was found that the longer reschedule intervals (for instance 160 sec vs. 40 sec) resulted in slightly higher message density on the channel. Typical results are plotted in figure 3.4-1, for a reschedule interval of 160 seconds. All curves start out for low message density situations with a normalized message delivery time of near one, due to the lack of collisions. As the message density increases on the channel, the systems with detection can avoid collisions and reschedule message traffic effectively to a point. However, at some point the ability of the system to deal with the message traffic fails, and message delivery time goes to infinity.

The following table shows the approximate message density which can be expected on a channel, based on the ability to detect collisions. A 0% collision performance means that a transmitter has no ability to monitor a channel, detect traffic, and delay its transmission accordingly. A 95% collision performance means that a transmitter can correctly detect and avoid collisions in 95% of the cases. Note that the 0% collision detection performance results in a maximum of 19% message density. This compares well with the theoretical limit of ALOHA CSMA, which is 18.4%.

Collision Detection Ability	Maximum Resulting Message Density
0%	19%
25%	23%
50%	28%
75%	42%
95%	64%

Table 3.4-1 Collision Detection Performance

Figure 3.4-1

CSMA DELIVERY TIME vs MESSAGE DENSITY
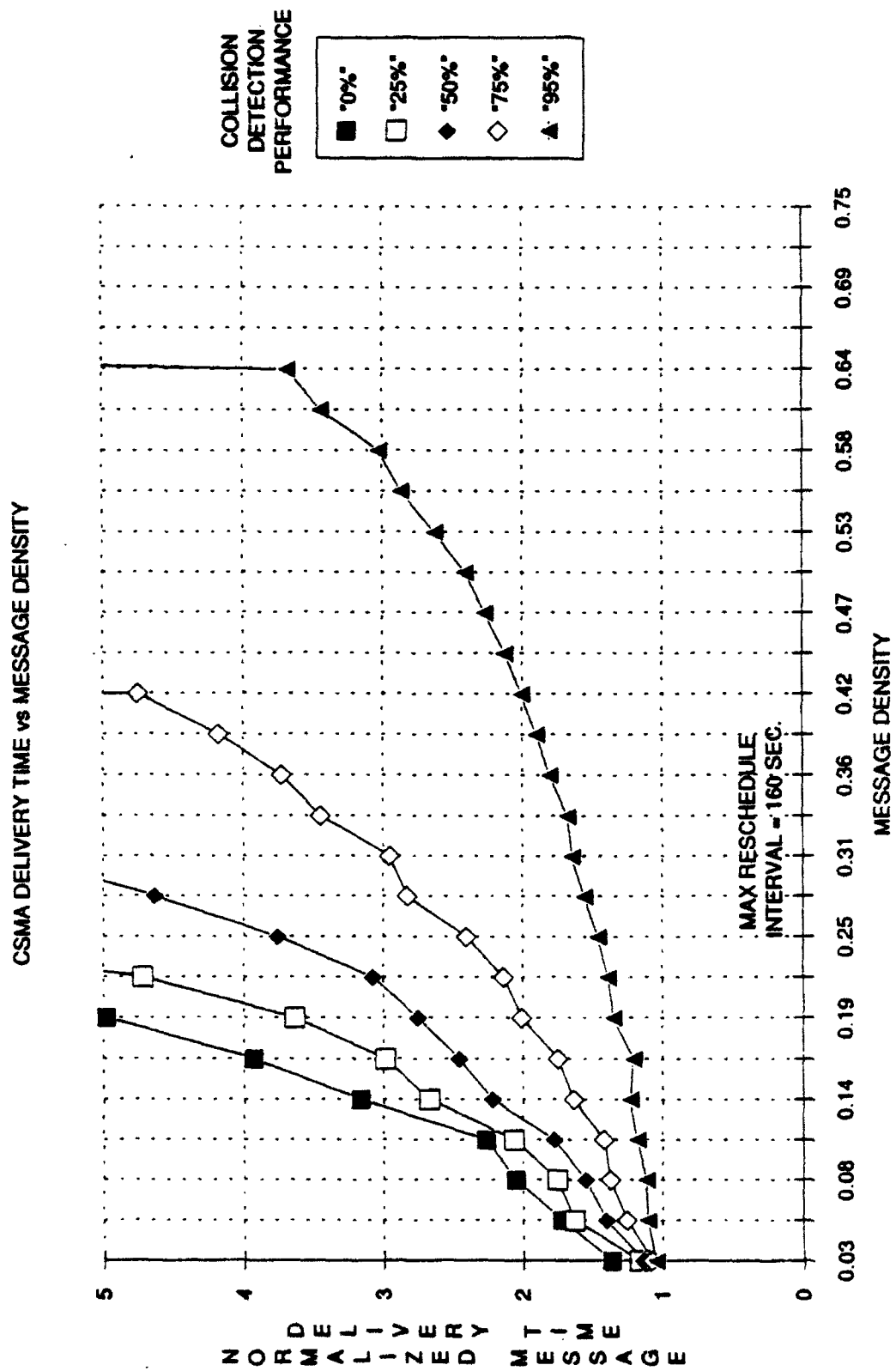
Conclusions:

1) The ability to avoid collisions has a significant effect on maximum message density. The result shows 95% accurate collision avoidance could support over double the message density supported at 50%.

2) the maximum reschedule interval had a small effect on message density. It should be set to at least the packet length times the maximum nodes that could be attempting to access the net at one time. Failure to do this results in a network that is unstable and could fail to get any messages through. A reasonable number is double this minimum.

3) the 12.5 MHz PC AT even with a math coprocessor is too slow to use for any simulation larger than this which requires multiple iterations at the packet level. Over 24 hours was required to generate the data for the figure 3.4-1.

4.0 IHFDN Simulator

The Computer Software Configuration Item (CSCI) developed under this program and described in this final report, is the IHFDN Simulator (INS). The Simulator is a tool that is used to determine the probable effects of various parameters on the performance of a given HF communications network. The network topology consists of up to 100 members distributed over a circular area up to 4,000 miles in radius. The Simulator calculates the network performance every 2 hours for a 24 hour period. Thus, starting at midnight, the first 2 hour interval ends at 2 AM. The second interval is from 2 AM to 4 AM and the 12th, or last, interval is from 10 PM to midnight. HF propagation predictions during these 2 hour intervals are based on IONCAP data. The INS presents the accumulated results in a clear and user friendly manner. The software resides and runs on an IBM PC compatible computer with a CGA or VGA color monitor and a Microsoft compatible serial 3-button mouse. For more information on the INS, consult the Software Design document, Users Manual, and Programmers Manual.

4.1 INS Introduction

The INS was created to provide a means of optimizing, bench marking, and demonstrating IHFDN concepts. The simulation uses closed form, numerical methods to determine network traffic characteristics, rather than simulation of individual packet by packet transmissions.

The design of the INS is based on techniques developed by the Government Systems Division of Harris Corporation for the AIRMICS Multimedia Network Design Study (ASQB-GC-90-002). The basic idea behind the approach, is that it is possible to numerically calculate the steady state performance of a network, if one knows the basic characteristics of the network:

- network topology
- message generation rates at each node
- throughput of each link
- error rate of each link
- delay in establishing a link between two nodes
- length of messages and acknowledgements

There are several advantages of the INS approach over standard packet by packet simulations:

- Steady state network characteristics are calculated in a single step, rather than the operator going through incremental iterations to locate network performance minimums and maximums.

- The speed of execution is orders of magnitude faster than traditional simulation

techniques (seconds vs. hours), allowing operators to use standard PC platform, rather than workstations, mainframes, etc., and...

-   The speed allows the operator to quickly gain results, then adjust the network, gain results, adjust the network, etc., optimizing network topologies or parameters, "on the fly".

-   The development cost of this approach is less than a traditional simulation, leaving more money available for algorithm development and performance bench marking.

This is not to say that the numerical methods will or should replace traditional simulation techniques, because they should not. The two techniques should be used together, and in the IHFDN, both the INS and the commercially available CACI COMNET II.5 simulation were used. COMNET II.5 served a "sanity check" for the INS, and provided detail performance results that the INS could not.

4.2 Design Description

The Communications Network Simulator architecture is a serial call tree structure. The figure below depicts the calling order of the components.

```
┌─────────────┐           ┌─────────────┐            ┌─────────────┐          ┌─────────────┐
│    USER     │ --------> │  CONFIGURER │ ---------> │   ROUTER    │ -------> │   ANALYZER  │
│  INTERFACE  │           │             │            │             │          │             │
└─────────────┘           └─────────────┘            └─────────────┘          └─────────────┘
```
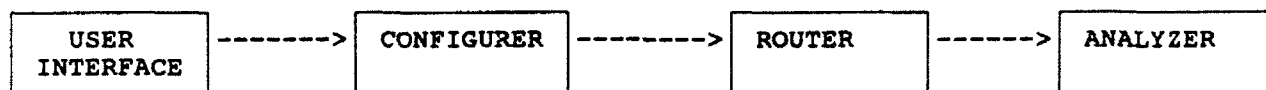
After initialization, the operator enters network and node parameters through the User Interface. The operator may then run the simulator. The first stage involves the User Interface calling the Configurer to set up the network environment for the first 2 hour interval. The Configurer then calls the Router to choose paths and message allocation given the network goals. Next, the Router calls the Analyzer to evaluate the network for the selected paths and message allocation. Control returns to the Router who decides whether or not the network can be tuned for greater performance. If it can, the Router modifies the path selection or the message allocation and calls the Analyzer to re-evaluate the network. This Router-Analyzer process repeats until the Router decides further modifications are fruitless and control is returned to the Configurer. The Configurer increments the time of day by two hours and the Configurer-Router-Analyzer process is repeated. The Configurer continues to increment the time of day and call the Router until time is greater than 24:00. After the network has been simulated for a 24 hour period, in 2 hour intervals, control is returned to

DATA READ & WRITES (GLOBAL)
(EXCLUDING INITIALIZATION)
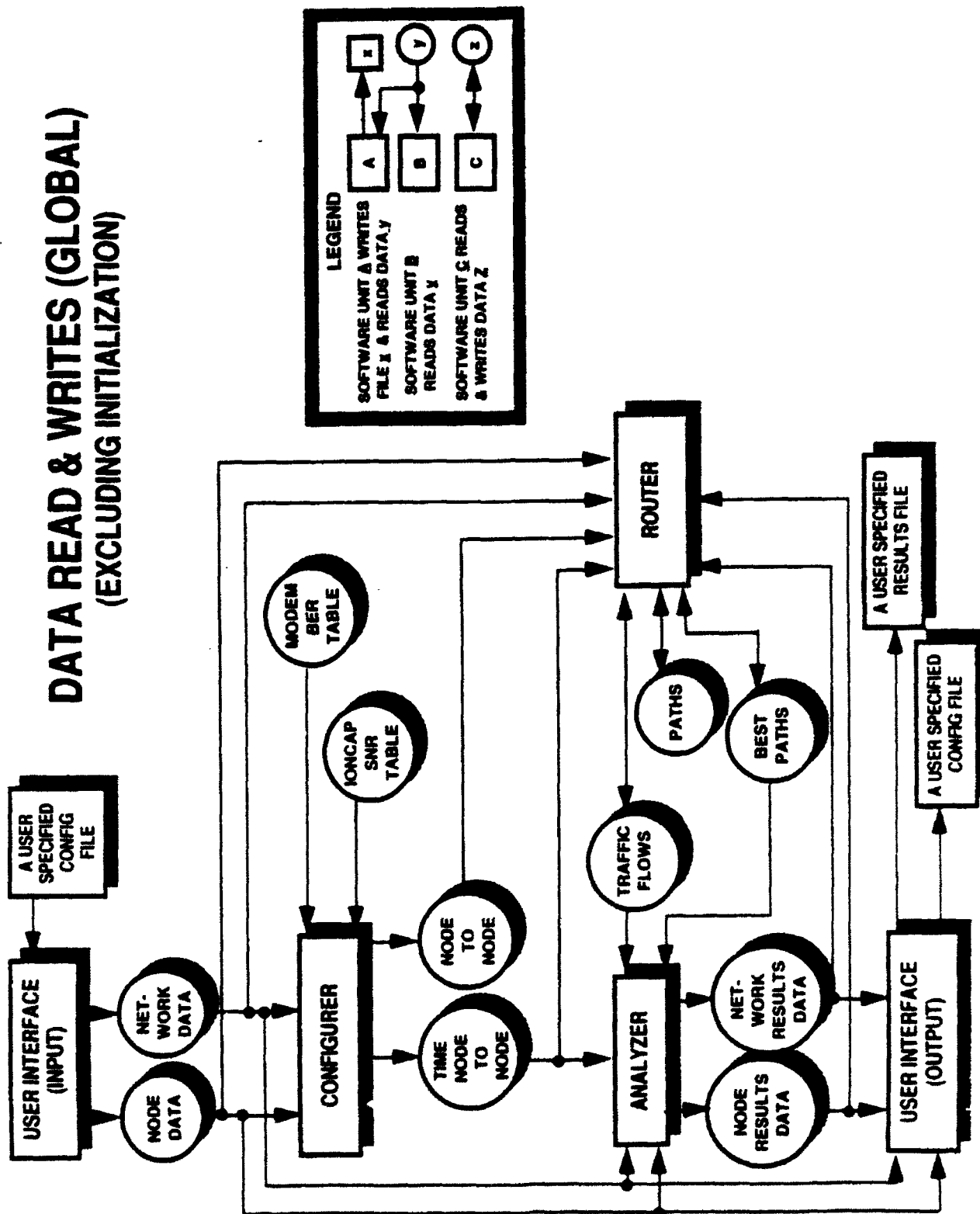
Figure 4.2-1

the User Interface and the operator can now view the results through the User Interface.

The Simulator is composed of 4 components: User Interface, Configurer, Router and Analyzer. Each component is described in the following sub-sections. (See figure 4.2-1)

4.2.1 User Interface Design Description

The User Interface Component is the start up, shutdown, user-interface and parent component. On start up, it initializes all global data. As the user-interface it provides the user with the ability to specify the parameters to be used in performing the simulation. In order to provide maximum flexibility, the user will be provided with the capability to save and edit the various configurations created. All user specified parameters shall be part of the saved configuration. Data entry windows allow the user to enter node and network information. All user specified parameters are stored in a global database for access by the other components of the simulator. The User Interface Component also allows the user to display results data from the Analyzer component.

4.2.2 Configurer Design Description

The Configurer Component uses the IONCAP SNR table, Modem bit error rate table, and user specified network and node data to generate the conditions to be simulated. The network conditions are expressed in terms of time independent and time dependent node-to-node data. Time independent data includes the distances, directions and rates of messages per hour between nodes. Time dependent data includes the network SNRs, probabilities of message error and selected bit rates between every pair of nodes.

4.2.3 Router Design Description

The Router software unit uses the IONCAP, Modem Bit Error Rate tables and the results of the Configurer Component to select paths and message allocation. Available network and node information will be used in least cost algorithms by the router to determine each path. Additionally, Node Results Data and Network Results Data for previous 2 hour run and/or previous iterations of the current 2 hour run from the Analyzer Component is utilize when applicable. If it is the first iteration of the first 2 hour run, then there will be no existing Results Data and Low LQA costs data is used.

4.2.4 Analyzer Design Description

The Analyzer software unit evaluates the network performance for the paths chosen by the

router. The results are expressed in terms of Node Results Data and Network Results Data.

4.3 Detailed Design

4.3.1 User Interface Detailed Design Description

The User Interface Component consists of the software for all graphics functions, data entry and display, and input and processing of user commands. The user makes selections on pull-down menus with the mouse. These selections either initiate commands or open data entry windows. Since the user interface already exists, this document will not go into as great detail as in the other components. The major functions of the User Interface include network data entry, node data entry, running a simulation, and providing simulation results data. (Figure 4.3.1-1)

4.3.1.1 User Interface Major Functionality

Network Data Entry

The operator selects Network Parameters and enters the following data:

Description	Data Field	Default
Network Name	Network_Data.Name	
Quality of Service Goal	Network_Data.Quality_Goal	low delay
Number of Nodes	Network_Data.Number_Nodes	10
Number of Nets	Network_Data.Number_Nets	5
Channel Type	Network_Data.Channel_Type	good
Channel Rank	Network_Data.Channel_Rank	1st
LQA Knowledge	Network_Data.LQA	high
LQA_Uncertainty*	Network_Data.LQA_Uncertainty	0
Traffic Length	Network_Data.Traffic_Length	60
Ack Length	Network_Data.Ack_Length	10
Global Arrival Rate*	Network_Data.Arrival_Rate	100
Sun Spot Number,Month	Network_Data.SSN_Month	10_JAN
TX Power Reduction	Network_Data.TX_Reduction	0
Noise Power Increase	Network_Data.Noise_Increase	0
Inter-net linking delay	Inter_Link_Delay	0
Intra-net linking delay	Intra_Link_Delay	0

* These fields are not currently defined, and are not part of the INS. For detail on the data presented here, see paragraph 3.5.11 of the Users Manual.

DATA INITIALIZATION (GLOBAL)

LEGEND

SOFTWARE UNIT G READS FILE S & WRITES DATA I
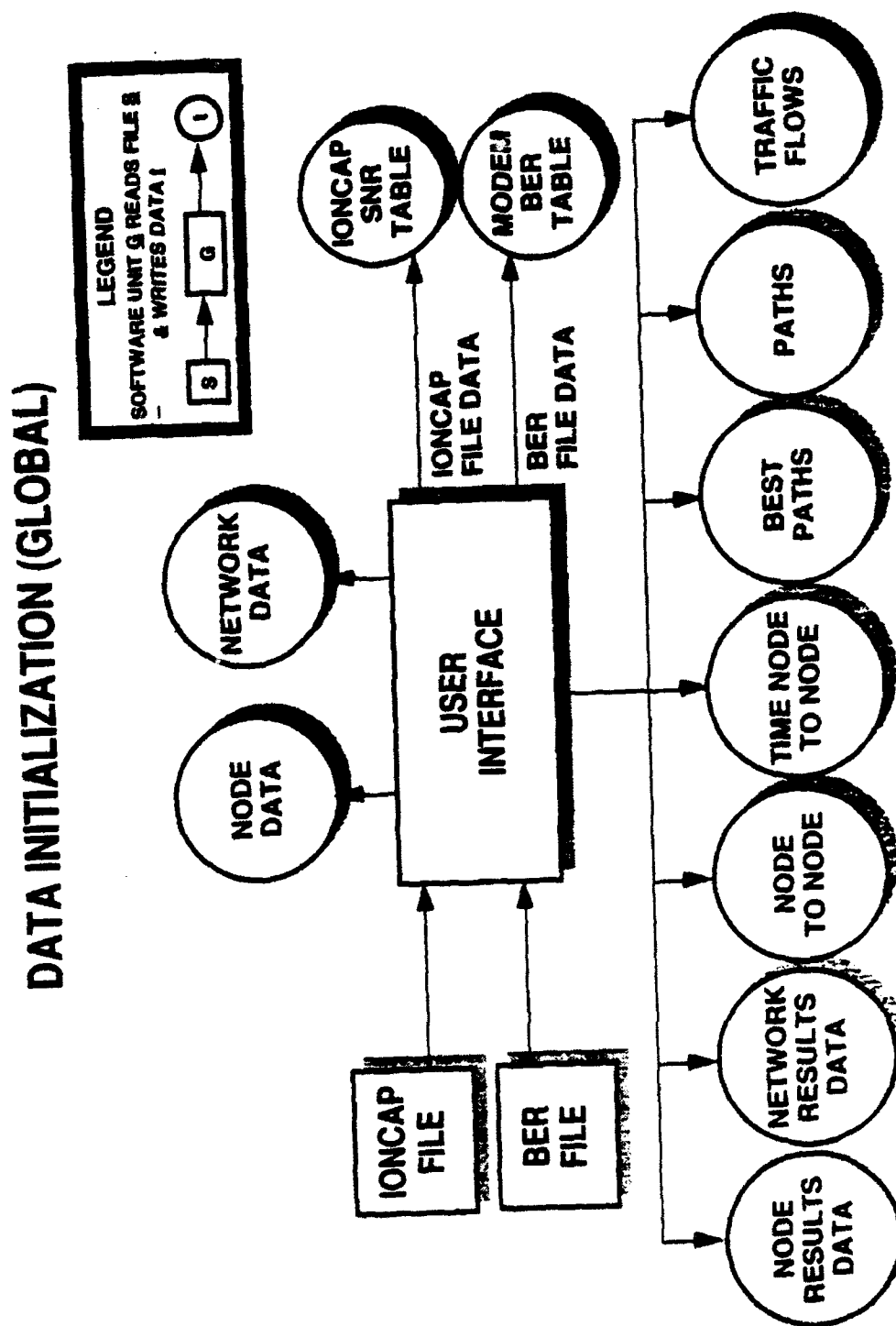
Figure 4.3.1-1

Node Data Entry

The operator selects Configure Network and adds nodes. Data is entered for every node in the network. When the user Adds a node, it is plotted and labelled on the map.

Description	Data Field	Default
Node Name	Node_Data[i].Name	
Net Number	Node_Data[i].Net	
Latitude	Node_Data[i].Latitude_Degrees	
	Node_Data[i].Latitude_Direction	South
Longitude	Node_Data[i].Longitude_Degrees	
	Node_Data[i].Longitude_Direction	East
Message Generation Rate	Node_Data[i].Generation_Rate	1000
Traffic Bandwidth	Node_Data[i].Bandwidth	300
Node Tx Reduction	Node_Data[i].TX_Reduction	0
Node Noise Increase	Node_Data[i].Noise_Increase	0
Number of Destinations	Node_Data[i].Number_Dests	
Destination Node Name*	Node_Data[i].Dests[j].Name	
% of i's Msgs to Destination*	Node_Data[i].Dests[j].Percent_Msgs	

* These fields are entered N times where N is the Number of Destinations from node i. When the operator specifies a destination node name, the User Interface searches Node_Data[k].Name, for all k, to see if the node already exists. If it does, then the value of k is used as the index j. If not, the node is created using the next unused i value and that index is used.

Running the INS

After entering the network and node parameters, the operator may choose to run the simulator. If the user selects RUN, the User Interface starts the INS and actions occur as covered in paragraph 3.1. Control is returned to the User Interface after the simulated "24 hour" run is completed. The INS runs in 2 hour increments based on IONCAP, so the operator can end a run after the first, second, or up to the eleventh 2 hour increment.

INS Results

After running the simulator, the operator may view the results that the Analyzer component calculated. The following network data is available for time t = 2 to 24 for each 2 hour increment:

Description	Data Field
# of msgs generated	Network_Results[t].Source
# of msgs through	Network_Results[t].Termination
Network reliability	Network_Results[t].Reliability
Network throughput	Network_Results[t].Throughput
Average network delay	Network_Results[t].Avg_Delay

The following node data is available for every node i where $1 \leq i \leq 100$, and for time, t, where $2 \leq t \leq 24$ for each 2 hour increment:

Description	Data Field
Rate traffic flows to i from other nodes	Node_Results[i,t].Inflow_Rate
Rate traffic flows from i to other nodes	Node_Results[i,t].Outflow_Rate
Outflow rate within i's net from i	Node_Results[i,t].Inter_Net_Outflow
Outflow rate outside i's net from i	Node_Results[i,t].Intra_Net_Outflow
Rate traffic originates at node i	Node_Results[i,t].Source_Rate
Rate traffic terminates at node i	Node_Results[i,t].Termination_Rate
Rate traffic flows through node i	Node_Results[i,t].Throughput
Error rate from i to all other nodes	Node_Results[i,t].Error_Rate
Expected # times a msg must be sent	Node_Results[i,t].Missed_Msg_Ratio
The effective traffic length	Node_Results[i,t].Adjusted_Length
Effective traffic flowing out of i	Node_Results[i,t].Service_Demand
% of i's bandwidth being used	Node_Results[i,t].Intensity
Time between receiving and sending msg	Node_Results[i,t].Delay
Aggregate rate of traffic loss at node i	Node_Results[i,t].Msg_Loss
Avg. time to send a msg from i to j	Node_Results[i,t].End_To_End_Delay[j]

User Interface Program Description Language

The high level mapping algorithm PDL is included here.

```
VARIABLE DECLARATIONS /**** MAPPING ALGORITHM ***********************
map_node (int i)

        int multiple, lat_index, long_index, table_step_degrees = 15;

        boolean lat_interpolate = true,
        long_interpolate = true;

        int    lat_degrees_1, lat_degrees_2,
                 vertical_1, vertical_2;

        int    long_degrees_1, long_degrees_2,
               horizontal_1, horizontal_2,
               horizontal_3, horizontal_4,
               temp_horizontal_1,
               temp_horizontal_2;

TABLE INITIALIZATION

        int    vertical_coordinate_table [2] [7] =

/*north*/    {{175, 143, 108,  76,  47,  28,  20},
/*south*/     {175, 207, 242, 274, 303, 322, 330}};

            /*  0    15   30   45   60   75   90
                            latitude */


        int    horizontal_coordinate_table [2] [7] [13] =

                        /* longitude direction = west */
 /*latitude*/
0     {{{320, 282, 250, 211, 170, 131,  96,  70,  38,   0,   0,   0,    0},
15      {320, 282, 253, 214, 170, 138, 102,  77,  48,  10,   0,   0,    0},
30      {320, 285, 253, 221, 182, 144, 115,  93,  61,  29,   0,   0,    0},
45      {320, 288, 259, 230, 195, 163, 138, 109,  77,  58,  26,   0,    0},
60      {320, 298, 269, 246, 218, 192, 166, 134, 102,  86,  64,  35,   35},
75      {320, 307, 285, 266, 246, 221, 186, 150, 118, 118, 118, 118,  118},
90      {320, 307, 285, 266, 246, 221, 186, 150, 118, 118, 118, 118,  118}}

    /*   0    15   30   45   60   75   90  105  120  135  150  165  180
                            longitude */

    /************************************************************************/

                        /* longitude direction = east */
 /*latitude*/
```

```
0        {{320, 349, 387, 419, 458, 499, 538, 573, 598, 630, 640, 640, 640},
15        {320, 349, 387, 416, 454, 499, 531, 566, 592, 621, 640, 640, 640},
30        {320, 349, 384, 416, 448, 486, 525, 554, 576, 608, 640, 640, 640},
45        {320, 349, 381, 410, 438, 474, 506, 531, 560, 592, 611, 640, 640},
60        {320, 349, 371, 400, 422, 451, 477, 502, 534, 566, 582, 605, 605},
75        {320, 349, 362, 384, 403, 422, 448, 483, 518, 550, 550, 550, 550},
90        {320, 349, 362, 384, .403, 422, 448, 483, 518, 550, 550, 550, 550}}
             };
      /*   0    15   30   45   60   75   90  105  120  135  150  165  180
                                longitude */
```

BODY

```
                /* FIND VERTICAL COORDINATE TABLE INDEX */

for (multiple = 0; multiple <= 6; multiple ++)
{

        if (node_data [i].latitude_degrees = multiple * table_step_degrees)
        {
             lat_index = multiple;
             lat_interpolate = false;
             break;
        }
        else if (node_data [i].latitude_degrees > multiple * table_step_degrees)

             lat_index = multiple;
}

/**** - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ****/
                /* CALCULATE VERTICAL COORDINATE */

if    (! lat_interpolate)
      node_data [i].vertical_coordinate =
                vertical_coordinate_table[node_data[i].latitude_direction]
                                                 [lat_index];

else  if(lat_interpolate)
{
      lat_degrees_1 = lat_index * table_step_degrees;
      lat_degrees_2 = (lat_index + 1)* table_step_degrees;
      vertical_1= vertical_coordinate_table [node_data[i].latitude_direction]
                                       [lat_index];
      vertical_2 = vertical_coordinate_table [node_data[i].latitude_direction]
                                       [lat_index + 1];
      node-data [i].vertical_coordinate =
         (node_data [i].latitude_degrees - lat_degrees_1)/
             (lat_degrees_2 - lat_degrees_1)
                *(vertical_2 - vertical_1) + vertical_1;
}
```

```
                    /* FIND HORIZONTAL COORDINATE TABLE INDEX */

for (multiple = 0; multiple <= 12; multiple ++)
{
        if (node_data[i].longitude_degrees = multiple * table_step_degrees)
        }
                long_index = multiple;
                long_interpolate = false;
                break;
        }
        else if (node_data[i].longitude_degrees > multiple * table_step_degrees)
                long_index = multiple;
}

/*** - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ***/

                    /* CALCULATE HORIZONTAL COORDINATE */

if (! long_interpolate)
{
        if (! lat_interpolate)
                node_data[i].horizontal_coordinate =
                        horizontal_coordinate_table[node_data[i].longitude_direction]
                                                    [lat_index]
                                                    [long_index];
        else
        {
                temp_horizontal_1 = horizontal_coordinate_table
                                        [node_data[i].longitude_direction]
                                            [lat_index]
                                            [long_index];
                temp_horizontal_2 = horizontal_coordinate_table
                                        [node_data[i].longitude_direction]
                                            [lat_index + 1]
                                            [long_index];
        }
}

else if (long_interpolate)
{
        horizontal_1 = horizontal_coordinate_table
                [node_data[i].longitude_direction][lat_index][long_index];
        horizontal_2 = horizontal_coordinate_table
                [node_data[i].longitude_direction][lat_index][long_index + 1];
        horizontal_3 = horizontal_coordinate_table
                [node_data[i].longitude_direction][lat_index + 1][long_index];
        horizontal_4 = horizontal_coordinate_table
                [node_data[i].longitude_direction][lat_index + 1][long_index + 1];

        long_degrees_1 = long_index * table_step_degrees;
        long_degrees_2 = (long_index+1)* table_step_degrees;
```

```
        temp_horizontal_1 =
                (node_data[i].longitude_degrees - long_degrees_1)/
                    (long_degrees_2 - long_degrees_1)
                        *(horizontal_2 - horizontal_1) + horizontal_1;

        temp_horizontal_2 =
                (node_data[i].longitude_degrees - long_degrees_1)/
                    (long_degrees_2 - long_degrees_1)
                        *(horizontal_4 - horizontal_3) + horizontal_3;
}

if (! lat_interpolate)
        node_data[i].horizontal_coordinate = temp_horizontal_1;

else
        node_data[i].horizontal_coordinate =
                (node_data[i].latitude_degrees - lat_degrees_1)/
                    (lat_degrees_2 - lat_degrees_1)
                        *(temp_horizontal_2 - temp_horizontal_1) + temp_horizontal_1;
```

4.3.1.2 User Interface Inputs/Outputs

The User Interface's inputs and outputs are global data elements that are respectively read or written. None are passed parameters.

Inputs are for all fields and indexes including i, j and t, where i is the source node index, j is the destination node index, and t is time:

IONCAP File Data
BER File Data
Network_Results[i,t]
Node_Results[i,t]

Outputs are for all fields and indexes including i, j and t, where i is the source node index, j is the destination node index, and t is time:

Network_Data
Node_Data[i]

The remaining output data structures/tables are written in the User Interface for initialization only.

IONCAP_SNR table
Modem_BER table
Time_Node_To_Node[i,j,t]
Node_To_Node[i,j]
Network_Results[i]
Node_Results[i,j]
Paths[i,j]
Best_Paths[i,j,t]
Traffic_Flows[i,j,t]

4.3.1.3 Mapping Algorithm

The Node Data Screen background is a map that has been scanned. Nodes are plotted on the map based on longitude and latitude. The node location is indicated as a dot and the 3 character node name is displayed in a text window directly above the dot. The mapping algorithm calculates the vertical and horizontal position on the screen. Interpolation is used when needed.

Vertical Coordinate

The vertical position is based on the latitude direction and degree.

```
Vertical_Coordinate_table [Node_Data[i].Latitude_Direction,
                           Node_Data[i].Latitude_Degrees]
```

Latitude	N	175	_._	108	76	47	28	20
Direction	S	175	207	242	274	303	322	330

```
          0    15   30   45   60   75   90
              Latitude Degrees
```

If the degree is between 0 and 90 inclusively, and a multiple of 15, then the vertical coordinate is a simple table look-up. Otherwise, interpolation is required:

Vertical_Coordinate =

$$\frac{\text{Node\_Data[i].Latitude\_Degrees - Lat\_Degrees\_1}}{\text{Lat\_Degrees\_2 - Lat\_Degrees\_1}} \times \text{(Vertical\_2 - Vertical\_1)} + \text{Vertical\_1}$$

Where Lat_Degrees_1 < Node_Data[i].Latitude_Degrees < Lat_Degrees_2
and Lat_Degrees_1 and Lat_Degrees_2 are two consecutive Latitude Degrees indexes of the Vertical_Coordinate_Table.

Where Vertical_1 and Vertical_2 are the two consecutive vertical coordinates in the Vertical_Coordinate_Table that are associated with Lat_Degrees_1 and Lat_Degrees_2, respectively, for Node_Data[i].Latitude_Direction.

Horizontal Coordinate

The horizontal position is based on the longitude degrees and direction, as well as the latitude degrees.

Horizontal_Coordinate_table [Node_Data[i].Longitude_Direction,
                        Node_Data[i].Latitude_Degrees,
                        Node_Data[i].Longitude_Degrees]

```
Longitude
Direction = West
```

Latitude Degrees	0	15	30	45	60	75	90	105	120	135	150	165	180
0	320	282	250	211	170	131	96	70	38	0	0	0	0
15	320	282	253	214	170	138	102	77	48	10	0	0	0
30	320	285	253	221	182	144	115	93	61	29	0	0	0
45	320	288	259	230	195	163	138	109	77	58	26	0	0
60	320	298	269	246	218	192	166	134	102	86	64	35	35
75	320	307	285	266	246	221	186	150	118	118	118	118	118
90	320	307	285	266	246	221	186	150	118	118	118	118	118

Longitude Degrees

```
Longitude
Direction = East
```

Latitude Degrees	0	15	30	45	60	75	90	105	120	135	150	165	180
0	320	349	387	419	458	499	538	573	598	630	640	640	640
15	320	349	387	416	454	499	531	566	592	621	640	640	640
30	320	349	384	416	448	486	525	554	576	608	640	640	640
45	320	349	381	410	438	474	506	531	560	592	611	640	640
60	320	349	371	400	422	451	477	502	534	566	582	605	605
75	320	349	362	384	403	422	448	483	518	550	550	550	550
90	320	349	362	384	403	422	448	483	518	550	550	550	550

Longitude Degrees

If both the latitude degrees and the longitude degrees are multiples of 15, then the horizontal coordinate is a simple table look-up. Otherwise, interpolation is necessary. The following are the steps required for interpolation.

First, Temp_Horizontal_1 is calculated for Lat_Degrees_1:

Temp_Horizontal_1 =

$$\frac{\text{Node\_Data[i].Longitude\_Degrees} - \text{Long\_Degrees\_1}}{\text{Long\_Degrees\_2} - \text{Long\_Degrees\_1}} \times (\text{Horizontal\_2} - \text{Horizontal\_1}) + \text{Horizontal\_1}$$

Next, Temp_Horizontal_2 is calculated for Lat_Degrees_2:

Temp_Horizontal_2 =

$$\frac{\text{Node\_Data[i].Longitude\_Degrees} - \text{Long\_Degrees\_1}}{\text{Long\_Degrees\_2} - \text{Long\_Degrees\_1}} \times (\text{Horizontal\_4} - \text{Horizontal\_3}) + \text{Horizontal\_3}$$

Where Long_Degrees_1 < Node_Data[i].Longitude_Degrees < Long_Degrees_2
and Long_Degrees_1 and Long_Degrees_2 are two consecutive Longitude Degrees indexes of the Horizontal_Coordinate_Table.

Where Horizontal_1 and Horizontal_2 are the two consecutive Horizontal coordinates in the Horizontal_Coordinate_Table that are associated with Long_Degrees_1 and Long_Degrees_2, respectively, for Lat_Degrees 1 and Node_Data[i].Latitude_Direction.

Where Horizontal_3 and Horizontal_4 are the two consecutive Horizontal coordinates in the Horizontal_Coordinate_Table that are associated with Long_Degrees_1 and Long_Degrees_2, respectively, for Lat_Degrees 2 and Node_Data[i].Latitude_Direction.

Where Lat_Degrees_1 < Node_Data[i].Latitude_Degrees < Lat_Degrees_2
and Lat_Degrees_1 and Lat_Degrees_2 are two consecutive Latitude Degrees indexes of the Horizontal_Coordinate_Table.

Finally, the Horizontal_Coordinate is calculated:

Horizontal_Coordinate =

$$\frac{\text{Node\_Data[i].Latitude\_Degrees} \quad - \quad \text{Lat\_Degrees\_1}}{\text{Lat\_Degrees\_2 - Lat\_Degrees\_1}} \times (\text{Temp\_Horizontal\_2-Temp\_Horizontal\_1}) + \text{Temp\_Horizontal\_1}$$

Where Lat_Degrees_1 < Node_Data[i].Latitude_Degrees < Lat_Degrees_2
and Lat_Degrees_1 and Lat_Degrees_2 are two consecutive Latitude Degrees indexes of the Horizontal_Coordinate_Table.

4.3.2 Configurer Detailed Design Description

The Configurer Component integrates network and node data along with IONCAP data and BER data to calculate node-to-node data, the bit rate per link, and the probability of message success between all nodes in the network. Figure 4.3.2-1 illustrates the steps in creating the message error rates between all nodes in the network. There are three types of input data for this process: data from off line IONCAP runs, user specified parameters, and modem performance characteristics (from off line).

The IONCAP data has been collected for twelve, two hour increments in a day, several distances up to 10,000 miles (north-south and east-west paths), three sun spot numbers (10, 110, 190), three channel ranks (best, second, third) and two months (July, January). IONCAP data has been tabulated to eliminate the need to run lengthy IONCAP simulations for each path (for example 100 nodes implies 9900 paths).

User specified parameters are: longitudes, latitudes, desired channel rank, power and noise levels adjustments, month, sun spot number, channel type, desired quality of service, and modem bit rates.

Modem bit rate tables contain bit error rate (BER) values for specific SNRS, modem bit rates, and channel conditions.

The first step in the process is to use the longitudes and latitudes to calculate the distances and approximate direction (N-S, E-W) between every two nodes in the network. Using these distances and directions, desired channel rank, month, and sun spot number, the IONCAP SNR tables can be accessed to extract the SNR between each two nodes in the network. These SNR values are then adjusted based on the input power and noise level adjustments.
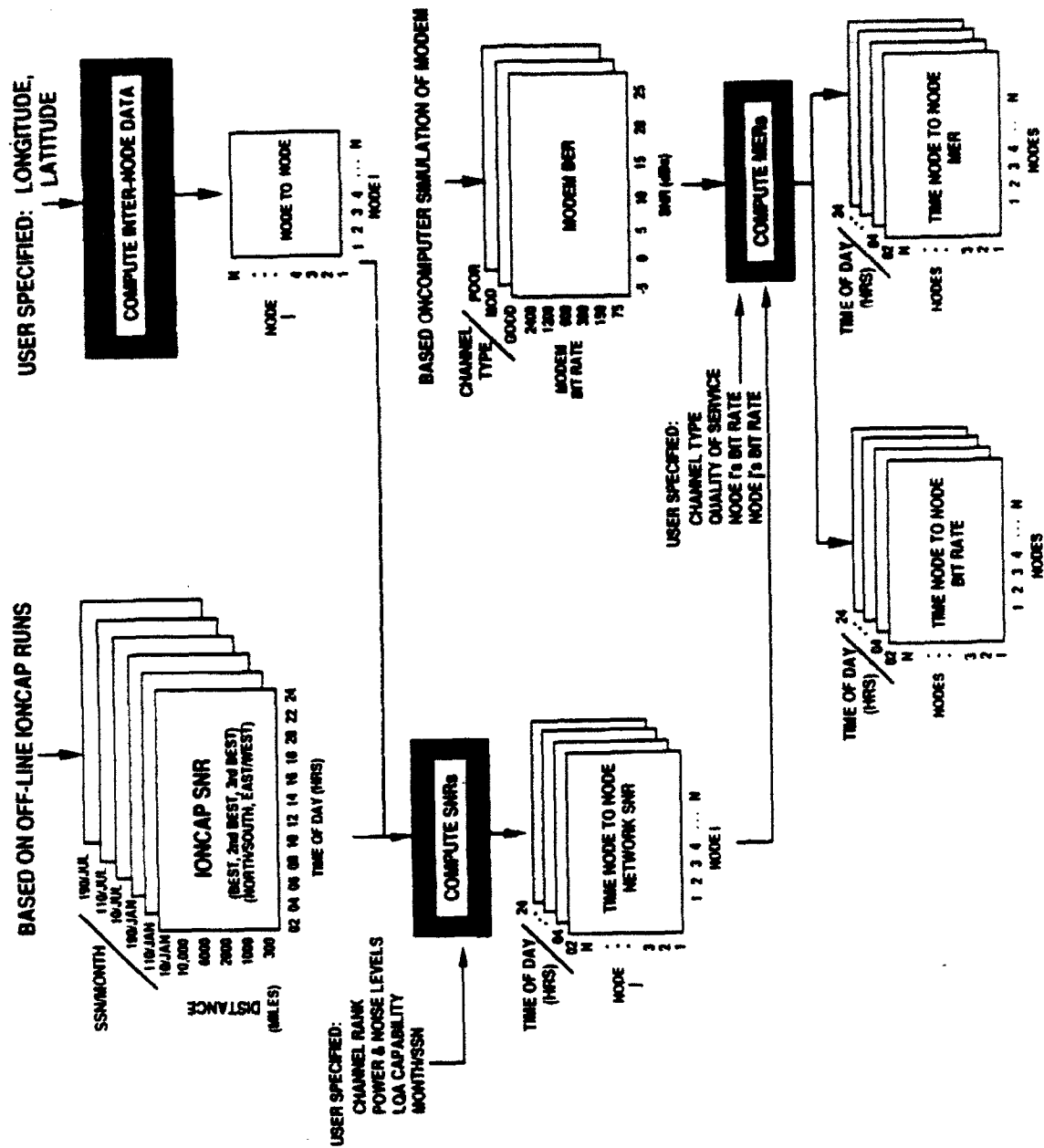
Figure 4.3.2-1

Given the node to node SNR tables, desired channel type, desired quality of service, and maximum modem bit rates, the Modem BER tables can be accessed. These tables are used to determine the appropriate modem data rate for each link, and the resulting modem BER for each link. Using the message lengths and the modem BER, node to node message error rates (MER) are be calculated. The Configurer is made up of 3 routines. They are Compute Inter-Node Data, Compute SNRs, and Compute MERs.

4.3.2.1 Compute Inter-Node Data Routine

Compute Inter-Node Data calculates the time independent node-to-node data. This data includes the distances, directions and rates of messages/hr between all nodes in the network.

Compute Inter-Node Data Inputs/Outputs

The inputs are for all i and j, where i is the source node and j is the destination node:

    Node_Data[i].Latitude_Degrees
    Node_Data[i].Latitude_Direction
    Node_Data[i].Longitude_Degrees
    Node_Data[i].Longitude_Direction
    Node_Data[i].Generation_Rate
    Node_Data[i].Destination[j].Percent_Msgs

The output is a global table for all i and j, where i is the source node index and j is the destination index:

    Node_To_Node[i,j].Distance
    Node_To_Node[i,j].Direction
    Node_To_Node[i,j].Msgs_Per_Hr

Compute Inter-Node Data Algorithms

The Great Circle Navigation algorithm based on the Spherical Triangle is used for calculating the distance S, between nodes 1 and 2 is:

```
S = 1/2 X 7915.6 X D X pi/180

Where  D = arc cos ( sin(y₁)sin(y₂) + cos(y₁)cos(y₂)cos(x₁ - x₂) )

And    y₁ = latitude of Node 1 in degrees
       y₂ = latitude of Node 2 in degrees
       x₁ = longitude of Node 1 in degrees
       x₂ = longitude of Node 2 in degrees

       y₁, y₂, x₁, and x₂ are signed integers with
            +y = northern latitude
            -y = southern latitude
            +x = eastern longitude
            -x = western longitude
```

The absolute direction between two nodes of either East-West or North-South is needed to index the IONCAP data. The algorithm for determining the direction between nodes Node 1 and Node 2 is:

```
If  |x₁ - x₂| > |y₁ - y₂| then direction is East-West
Else if |x₁ - x₂| = |y₁ - y₂| then direction is East-West
Else if |x₁ - x₂| < |y₁ - y₂| then direction is North-South

Where y₁ = latitude of Node 1 in degrees
      y₂ = latitude of Node 2 in degrees
      x₁ = longitude of Node 1 in degrees
      x₂ = longitude of Node 2 in degrees

      y₁, y₂, x₁, and x₂ are signed integers with
           +y = northern latitude
           -y = southern latitude
           +x = eastern longitude
           -x = western longitude
```

The number of messages from source node i to destination node j is equal to the message generation rate of i multiplied by the percentage of i's messages going to j.

```
# msgs from i to j = i's msg generation rate  x  % i's msgs going to j
```

4.3.2.2 Compute SNRs

Compute calculates the Signal-to-Noise Ratio for communication between every pair of nodes in the network.

Compute SNRs Inputs/Outputs

The inputs are for all i and j, where i is the source node index and j is the destination node index:

Network_Data.Channel_Rank
Network_Data.Time
Network_Data.SSN_Month
Network_Data.TX_Reduction
Network_data.Noise_Increase

Node_Data[i].TX_Reduction
Node_Data[i].Noise_Increase

Node_To_Node[i,j].Distance
Node_To_Node[i,j].Direction

IONCAP_SNR table

The output is for all i and j, where i is the source node index and j is the destination node index:

Time_Node_To_Node.Network_SNR   [i,j,Network_Data.Time]

Compute SNRs Algorithms

The SNR interpolation algorithm for nodes x and y with a separation distance of d is:

$$SNR_{xy} = \frac{d - d_1}{d_2 - d_1} (SNR_2 - SNR_1) + SNR_1 - L_{tx} - L_{rx} - l_{tx} - l_{rx}$$

Where $d_1 < d < d_2$, and d_1 and d_2 are contiguous distances of IONCAP_SNR.

Where SNR_1 is the value in IONCAP_SNR_table for distance d_1 and SNR_2 is the value in IONCAP_SNR_table for distance d_2.

Where L_{tx} and L_{rx} are respectively the Network transmit power level reduction and receive noise level increase.

Where l_{tx} is the transmit power level reduction for the transmitting node, and l_{rx} is the receive noise level increase for the receiving node.

If d < smallest distance in the table, then SNR_{xy} = the SNR for the smallest distance in the table.
If d > largest distance in the table, then SNR_{xy} = the SNR for the largest distance in the table.

4.3.2.3 Compute MERs

Compute MERS calculates the probable Message Error Rates and saves the associated modem bit rate for every pair of nodes in the network.

Compute MERs Inputs/Outputs

The inputs are for all i and j, where i is the source node index and j is the destination node index:

> Network_Data.Time
> Network_Data.Channel_Type
> Network_Data.Quality_Goal
> Network_Data.Traffic_length
>
> Node_Data[i].Bandwidth
> Node_Data[j].Bandwidth
>
> Time_Node_To_Node.[i,j,Network_Data.Time].Network_SNR
>
> Modem_BER [Network_Data.SNR,
>   Network_Data.Modem_Bit_Rate,
>   Network_Data.Channel_Type]

The outputs are for all i and j, where i is the source node index and j is the destination node index:
> Time_Node_To_Node[i,j,t].MER
> Time_Node_To_Node[i,j,t].Bit_Rate

Compute MERs Algorithms

The message error rate is derived from the bit error rate for the link on which the message travels. The modem Bit Rate probability table is indexed by SNR, Modem Bit Rate and Channel Type. Channel Type and Modem Bit Rate are user specified. SNR was previously calculated and will need interpolation if it is not between -5 and 25 inclusively, and a multiple of 5. The Modem Bit Rate indicates the maximum bit rate of the transmitting node i. The BER is looked-up or calculated using the maximum bit rate, and then using consecutively lower bit rates until a tolerable BER is reached. Whether or not a BER is tolerable is dependent upon the Network's LQA quality of service goal:

Service Goal	Worst Tolerable BER
low delay	1×10^{-3}
high reliability	1×10^{-4}
high throughput	1×10^{-3}
LPE/LPD	1×10^{-4}

If interpolation is required, the BER algorithm for nodes i and j with a signal to noise ratio of SNR is:

$$BER = \frac{SNR - SNR_1}{SNR_2 - SNR_1} (BER_2 - BER_1) + BER_1$$

Where $SNR_1 < SNR < SNR_2$, and SNR_1 and SNR_2 are contiguous SNRs in Modem_BER.

Where BER_1 is the value in BER_table for SNR s_1 and BER_2 is the value in BER_table for SNR_2.

If SNR < smallest SNR in the table, then BER_{ij} = the BER for the smallest SNR in the table.

If SNR > largest SNR in the table, then BER_{ij} = the BER for the largest SNR in the table.

The probability of Message Error algorithm for a message from node x to y of m bits long with a bit error rate of BER :

$$Msg\ Error_{xy} = 1 - (1 - BER)^m$$

Where a message error occurs if it contains one or more bit errors.

4.3.3 Router Detailed Design Description

The Router software unit determines the percentage of messages to be transmitted over each link. The Router uses network data, node data and LQA tables to help determine the routing. Different types of data are available to the Router depending on what LQA capability is specified. The first try of each time period is by definition limited to Low LQA capabilities. Subsequent tries may utilize High LQA capabilities if so specified by the user.

		Primary Path Cost Component	
Quality of Service	Goal	Low LQA	High LQA
low delay	min delay	# of hops, H	calculated delays
high reliability	min msg loss	longest hop, D	msg_lost
high throughput	max throughput	H / D	1 / calc throughput
LPE/LPD	min tx power	H x D	link SNRs

4.3.3.1 Router PDL

Create All Paths

```
Create_All_Paths()

begin
  for i = 1 to Network_Data.Number_Nodes do
    for j = 1 to Network_Data.Number_Nodes do

      /* 1 hop path */
      Create_1_Hop_Path (path,i,j);
      Insert_By_Cost (path,path_head);

      /* 2 hop paths */
      for k = 1 to Network_Data.Number_Nodes do
        if (Node_Data[k].Net <> Node_Data[i].Net) and
           (Node_Data[k].Net <> Node_Data[j].Net)
        then Create_2_Hop_Path (path,i,k,j);
             Insert_By_Cost (path,path_head);
```

```
/* 3 hop paths */
 for k = 1 to Network_Data.Number_Nodes do
   if (Node_Data[k].Net <> Node_Data[i].Net) and
      (Node_Data[k].Net <> Node_Data[j].Net)
   then for m = 1 to Network_Data.Number_Nodes do
      if (Node_Data[m].Net <> Node_Data[i].Net) and
         (Node_Data[m].Net <> Node_Data[j].Net) and
         (Node_Data[m].Net <> Node_Data[k].Net
      then Create_3_Hop_Path (path,i,k,m,j);
           Insert_By_Cost (path,path_head);
           Create_3_Hop_Path (path,i,m,k,j);
           Insert_By_Cost (path,path_head);
```

Router Inputs/Outputs

The inputs are for all i and j, where i is the source node index, j is the destination node index and t is time:

>   Network_Data
>   Node_Data[i]
>   IONCAP_SNR table
>   Modem_BER table
>   Node_To_Node[i,j]
>   Time_Node_To_Node[i,j,t]
>   Network_Results[t]
>   Node_Results[i,t]

The outputs are for all i and j, where i is the source node index, j is the destination node index and t is time:

>   Paths[i,j]
>   Best_Paths[i,j,t]
>   Traffic_Flows[i,j,t]

Router Algorithms

This function creates a static structure that remains the same for 24 hour simulation run. For every origin node i and destination node j, it creates a linked list of all possible 1, 2 and 3 hop paths. See figure 4.3.3-1. It is restricted that a given path will not visit a net more than once. When creating a path, nodes are randomly chosen from within a net. At the time of path creation, Low LQA costs (see section 4.3.3) are calculated based on the input quality of service and the paths are ordered with the least expensive path at the front of the list and the most expensive at the end of list.

ROUTER STRUCTURE (FOR ONE PATH)
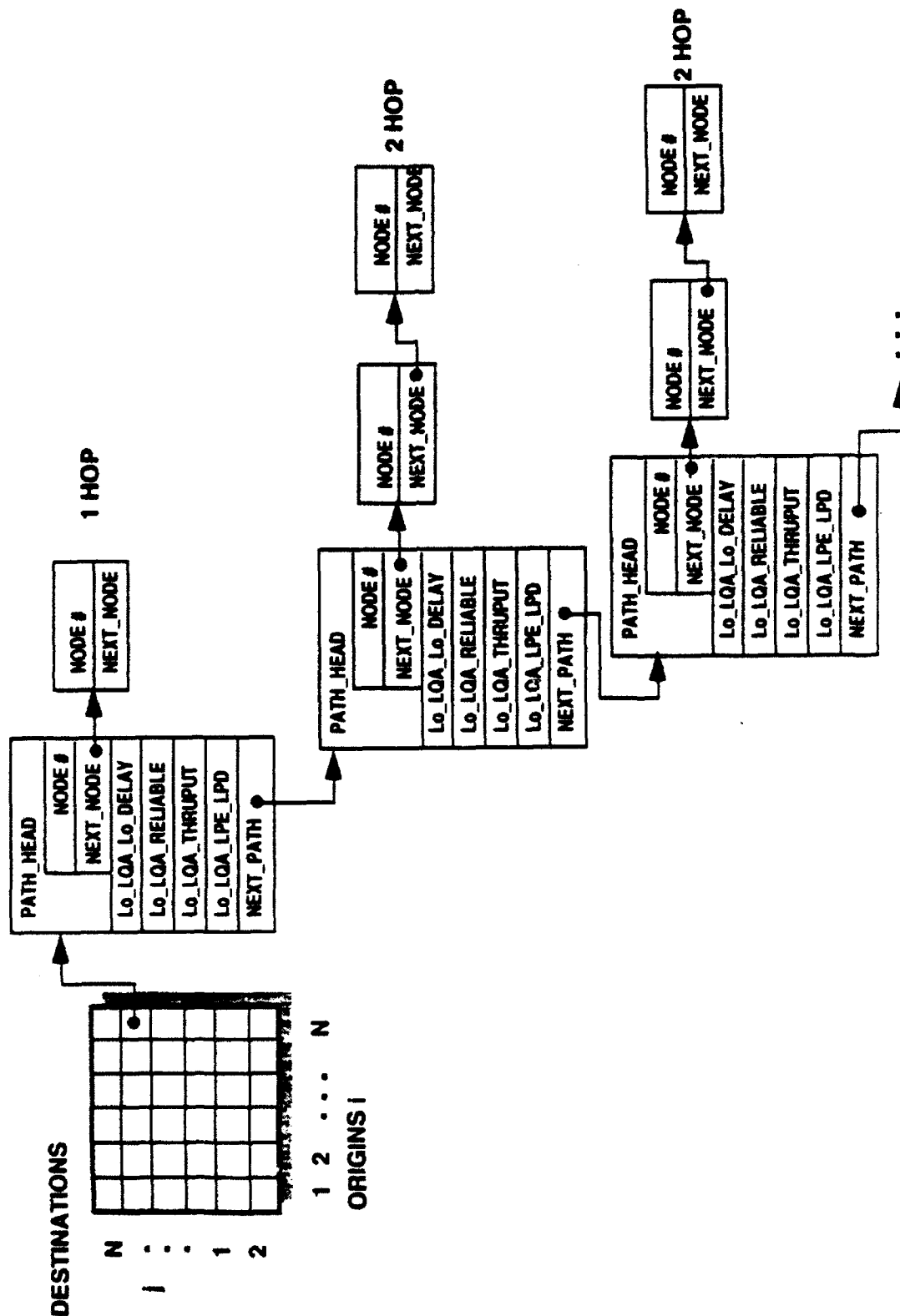
Figure 4.3.3-1

4.3.4 Analyzer Detailed Design Description

The Analyzer component evaluates the network performance based on the paths and message allocation chosen by the Router.

4.3.4.1 Analyzer PDL

```
Analyzer(t:Time)

begin
   /* Calculate Node Results Data ************************************************
   for i = 1 to Network_Data.Number_Nodes do

        /* Inflow Rate
        Node_Results[i,t].Inflow_Rate = 0;
        for k = 1 to Network_Data.Number_Nodes do
                Node_Results[i,t].Inflow_Rate = Node_Results[i,t].Inflow_Rate +
                                                Traffic_Flows[k,i,t];

        end for k;

        /* Source Rate
        Node_Results[i,t].Source_Rate = 0;
        for j = 1 to Network_Data.Number_Nodes do
                Path = Best_Paths[i,j,t];
                While Path <> NIL Do
                    Node_Results[i,t].Source_Rate = Node_Results[i,t].Source_Rate +
                                     Path^.Alloc[Path^.Alloc_Method];
                    Path = Path^.Next_Path;
                End While Path;
        end for j;

        /* Termination Rate
        Node_Results[i,t].Termination_Rate = 0;
        for k = 1 to Network_Data.Number_Nodes
                Path = Best_Paths[k,i,t];
                While F.ch <> NIL Do
                    Node_Results[i,t].Termination_Rate =
                                     Node_Results[i,t].Termination_Rate +
                                     Path^.Alloc[Path^.Alloc_Method];
                    Path = Path^.Next_Path;
                End While Path;
        end for k;
```

```
      /* Throughput
      Node_Results[i,t].Throughput = Node_Results[i,t].Inflow_Rate +
                                      Node_Results[i,t].Source_Rate;
/* Outflow Rate, Inter-Net Outflow rate, Intra-Net Outflow rate, Error Rate
      Node_Results[i,t].Outflow_Rate = 0;
      Node_Results[i,t].Inter_Net_Outflow = 0;
      Node_Results[i,t].Intra_Net_Outflow = 0;
      Node_Results[i,t].Error_Rate = 0;
      for j = 1 to Network_Data.Number_Nodes do
            Node_Results[i,t].Outflow_Rate = Node_Results[i,t].Outflow_Rate +
                                              Traffic_Flows[i,j,t];
            If Node_Data[i].Net = Node_Data[j].Net then
               Node_Results[i,t].Intra_Net_Outflow =
                               Node_Results[i,t].Intra_Net_Outflow +
                               Traffic_Flows[i,j,t]
            Else
               Node_Results[i,t].Inter_Net_Outflow =
                               Node_Results[i,t].Inter_Net_Outflow +
                               Traffic_Flows[i,j,t]
            End If-Else;
            Node_Results[i,t].Error_Rate = Node_Results[i,t] +
                        (Time_Node_To_Node[i,j].MER * Traffic_Flows[i,j,t]);
      end for j;
      Node_Results[i,t].Error_Rate = Node_Results[i,t] /
            Node_Results[i,t].Throughput;
      /* Missed Message Ratio
      Node_Results[i,t].Missed_Msg_Ratio =
                               (1 - Node_Results[i,t].Error_Rate) ** -1;

      /* Adjusted Message Length
      Node_Results[i,t].Adjusted_Length = (Network_Data.Traffic_Length *
                                     Node_Results[i,t].Missed_Msg_Ratio)
                                  + ((Node_Results[i,t].Inflow_Rate /
                                        NetworK_Data.Traffic_Length)
                                     * Network_Data.Ack_Length);
      /* Service Demand
      Node_Results[i,t].Service_Demand = (Node_Results[i,t].Outflow_Rate /
                                     Network_Data.Traffic_Length) *
                                     Node_Results[i,t].Adjusted_Length;

      /* Intensity
      Node_Results[i,t].Intensity    =    Node_Results[i,t].Service_Demand    /
                                     Node_Data[i].Bandwidth;

      /* Linking Delay
      Node_Results[i,t].Linking_Delay = (Node_Results[i,t].Intra_Net_Outflow /
                                     Node_Results[i,t].Outflow_Rate *
                                     Network_Data.Intra_Net_Delay)
                                  + (Node_Results[i,t].Inter_Net_Outflow /
                                     Node_Results[i,t].Outflow_Rate *
                                     Network_Data.Inter_Net_Delay)
```

```
    /* Delay
    Node_Results[i,t].Delay = (Node_Results[i,t].Intensity /
                               (1 - Node_Results[i,t].Intensity)) *
                               (Network_Data.Traffic_Length /
                                Node_Data[i].Bandwidth) +
                                Node_Results[i,t].Linking_Delay;


    /* Message Loss
    Node_Results[i,t].Msg_Loss = Node_Results[i,t].Service_Demand -
                                 Node_Data[i].Bandwidth;
    /* End to End Delay
    for j = 1 to Network_Data.Number_Nodes
       Node_Results[i,t].End_To_End_Delay[j] = 0;
       path_delay = 0;
       total_path_flow = 0;
       path = Best_Paths[i,j,t];
       While path <> NIL do
           node = path^.path_head;
           While node.next_node <> NIL Do
               path_delay = path_delay + Node_Results[node^.node].Delay;
               node = node^.next_node;
           End While node;
           Node_Results[i,t].End_To_End_Delay[j] =
                   Node_Results[i,t].End_To_End_Delay[j] +
                   ( path_delay * node^.Alloc[node^.Alloc_Method]);
           total_path_flow = total_path_flow + node^.Alloc[node^.Alloc_Method];
           path = path^.next_path;
       end while path;
       Node_Results[i,t].End_To_End_Delay[j] =
               Node_Results[i,t].End_To_End_Delay[j] / total_path_flow;
    end for j;

end for i;

/* Calculate Network Results data *****************************************

/* Network Source Rate and Termination Rate
Network_Results[t].Source_Rate = 0;
Network_Results[t].Termination_Rate = 0;
for i = 1 to Network_Data.Number_Nodes do
   Network_Results[t].Source_Rate = Network_Results[t].Source_Rate +
                                    Node_Data[i].Source_Rate;
   Network_Results[t].Termination_Rate = Network_Results[t].Termination_Rate
                        +       Node_Data[i].Termination_Rate;
end for i;

/* Network Reliability
Network_Results[t].Reliability = Network_Results[t].Source_Rate /

   Network_Results[t].Termination_Rate
      /* Network Throughput
Network_Results[t].Throughput = Sum of all path_Results.Throughput

/* Network Throughput
Network_Results[t].Throughput = Sum of all path_Results.Throughput
```

```
/* Network Average Delay
Network_Results[t].Avg_Delay = 0;
for i = 1 to Network_Data.Number_Nodes do
    for j = 1 to Network_Data.Number_Nodes do
        Network_Results[t].Avg_Delay = Network_Results[t].Avg_Delay +
                    Node_Results[i,t].End_To_End_Delay[j];
    end for j;
end for i;
Network_Results[t].Avg_Delay = Network_Results[t].Avg_Delay /
            Network_Data.Number_nodes;


End Analyzer;
```

4.3.4.2 Analyzer Inputs/Outputs

The inputs are:

Network_Data.Arrival_Rate
Network_Data.Traffic_Length
Network_Data.Ack_length

Node_Data[i].Bandwidth
Node_Data[i].Error_Rate
Node_Data[i].Generation_Rate

Time_Node_To_Node[i,j].MER

Best_Paths[i,j,Network_Data.Time]
Traffic_Flows[i,j,Network_Data.Time]

The outputs are:

Network_Results[Network_Data.Time]
Node_Results[i,Network_Data.Time]

4.3.4.3 Analyzer Algorithms

In the following algorithms, i is a source node and j is a destination node.   Figure 4.3.4-1 illustrates the nature of flows through a node.

Node Results Algorithms

Inflow Rate for node j = The Sum of Traffic_Flow [i,j,time] from all i

Outflow Rate for node i = The Sum of Traffic_Flow [i,j,time] to all j

Intra-Net Outflow Rate for node i = The Sum of Traffic Flow [i,j,time] to all j within i's net.

Inter-Net Outflow Rate = The Sum of Traffic Flow [i,j,time] to all j outside i's net.

Source Rate = Rate at which traffic originates at node i.

TRAFFIC INFLOW/OUTFLOW AT A NODE

STATION THROUGHPUT = STATION THROUGHPUT
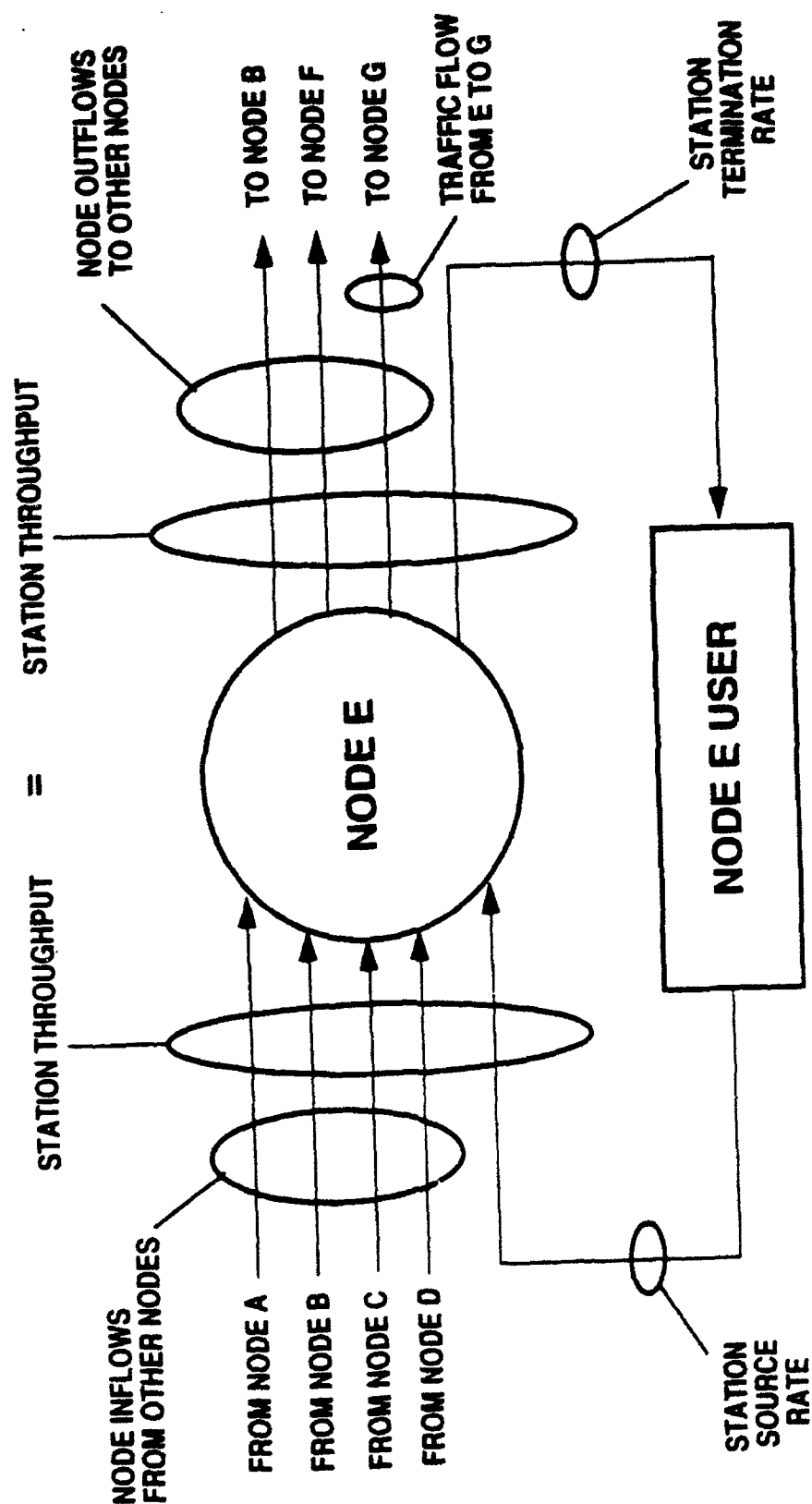
Figure 4.3.4-1

Termination Rate = Rate at which traffic terminates at node i.

Throughput = Inflow Rate + Source Rate [i]

Error Rate = $\dfrac{\text{Sum of Message Error Rate[i,j]} \times \text{Traffic Flow[i,j,time] for all j}}{\text{Throughput}}$

Missed Message Ratio = $(1 - MER)^{-1}$

Adjusted Length = Traffic Length × Missed Message Ratio

$$+ \dfrac{\text{Inflow Rate}}{\text{Traffic Length}} \times \text{Ack Length}$$

Service Demand = $\dfrac{\text{Outflow Rate}}{\text{Traffic Length}} \times \text{Adjusted Length}$

Intensity = Service Demand ÷ Traffic Bandwidth

Linking Delay = $\dfrac{\text{Intra-Net Outflow Rate}}{\text{Outflow Rate}} \times \text{Intra-Net Delay}$

$$+ \dfrac{\text{Inter-Net Outflow Rate}}{\text{Outflow Rate}} \times \text{Inter-Net Delay}$$

Delay = $\dfrac{\text{Intensity}}{1 - \text{Intensity}} \times \dfrac{\text{Traffic Length}}{\text{Traffic Bandwidth}} + \text{Linking Delay}$

Msg Loss = Service Demand - Traffic Bandwidth

4.4 Bench Tests

The purpose of this section of the final report is to compare and contrast the Improved HF Data Network Simulator (INS) and CACI Products Company's COMNET II.5.

4.4.1 CACI/INS Feature Comparison

First, the general approach to network simulation and the associated run-time attributes of each simulator are compared.

4.4.1.1 User Interface

COMNET II.5 offers separate environments for the entry of network parameters, the simulation of the network, and the viewing of simulation results. All of these environments run under a single shell executed by typing "netlab" in the appropriate directory. The network parameter entry environment, COMNETIN, allows the user to enter all nodal, link, message, and run-time default simulation parameters. The location of objects during the display of the network configuration is determined by the user and may be changed as desired as there is no concept of longitude and latitude inherent to this modeling tool.

Once the network configuration has been verified, the user may run a simulation of the model. Verification is done while in the COMNETIN environment, but the simulation is run from either the COMNET or COMNETIN environments. COMNET generates results in the form of text files with the elapsed time displayed during simulation to indicate progress. COMNETIN not only generates a results text file, but it also animates the simulation by displaying the network configuration and the message flows as they occur.

INS offers a single environment for the entry of network parameters, the simulation of the network, and the viewing of the simulation results. Network parameters, those parameters that apply to the network as a whole, and nodal parameters are entered by the user. Link parameters are not entered by the user as they are developed during simulation by INS as the result of consulting IONCAP and Modem BER tables.

Again, INS simulates the network configuration within the same environment as network parameters are entered. The network configuration is verified when simulation is requested. Once verification is complete, the network is simulated and the results are stored in binary files. INS does not offer an animation feature to demonstrate actual network operation, but a subset of the results data is available for viewing within the INS environment with all results data viewable through any standard text editor.

4.4.1.2 Network Simulation

COMNET II.5 uses discrete event simulation as an approach to network simulation, meaning that messages are placed in simulated queues, transmitted over simulated links, received at intermediate nodes, and finally removed from the system when the message is received at the intended destination. INS uses an analytical model as an approach to network simulation. This model, based on the M/M/1 queuing model, does not actually generate and send messages but rather applies statistical methods to determine the expected network performance at any given snapshot in time. This means that an INS run occurs at constant values IONCAP and MODEM BER determined by the 2 hours time interval chosen, the SSN and the time of year.

As COMNET II.5 is intended to be used in a broad range of network simulation applications, it allows the user to specify all network characteristics including node-to-node link characteristics. Consequently, COMNET II.5 requires the operator to thoroughly investigate link attributes outside of the COMNET II.5 environment when trying to simulate any network. INS. specifically designed for use in simulating HF Data Networks, incorporates IONCAP and Modem BER data for use in developing link characteristics and preferred path selections. The link characteristics determined by INS where used as input data into COMNET II.5 during benchmarking as COMNET II.5 can not make use of raw IONCAP data.

Because of COMNET II.5's broad application base, COMNET II.5 has extensive network overhead attributes. These include the possible introduction of frame and packet headers, and retry algorithms into the model. INS does not offer a breakout of header sizes or retry algorithms. Messages are of a fixed size during any given simulation and are specified as a size inclusive of headers, baseband data, and other message overhead. Acknowledgments are treated separately in INS and the user may specify the size of an acknowledgment message. INS' retry algorithm is simple continued transmission of a message until that message is received at the intended node. Since INS is an analytical model, messages are not actually sent repeatedly but the expected results of repeated transmissions are statistically determined.

COMNET II.5 allows the user to specify both nodal processing delays and link delays. When nodal processing delays are specified, COMNET II.5 views nodal processing as a queue where messages are stored until they are able to be processed, and as a processing or servicing agent, resident within the node, to service the queue. Additionally, each node is considered to have an outgoing queue associated with each link, where the link acts as the servicing agent for that queue. INS considers a node and it's associated links to represent a single queue and a single processing agent whose service rate is a composite rate calculated on the node's modem capabilities and the associated link's characteristics.

4.4.2 CACI/INS Simulation Data Comparison

The same network configurations where simulated by both COMNET II.5 and INS in an effort to compare and contrast results and to accomplish a "sanity" check of INS. The delay metric was chosen as the network optimization goal as it is a metric inherent to both simulator implementations. Note that the Modem BER table used by INS for this benchmarking was the table used for software test purposes and is not the table used in the final version of INS. Older versions of INS may be used to repeat these tests or the COMNET II.5 configuration files may be updated to reflect the revised link characteristics.

4.4.2.1 Message Delays

Identical network configurations were simulated using COMNET II.5 and INS. The network configuration is shown in Figure 4.2.2-1 and the resulting delays are shown in Table 4.2.2-1 The actual results files can be seen in Appendix A. As it can be seen, there was no correlation of delays between the two simulators for a simple network.

- - - - - - - - - - - - - ->

Message = 600 Bits / Message inter-arrival time = 1 second (Exponential Distribution)
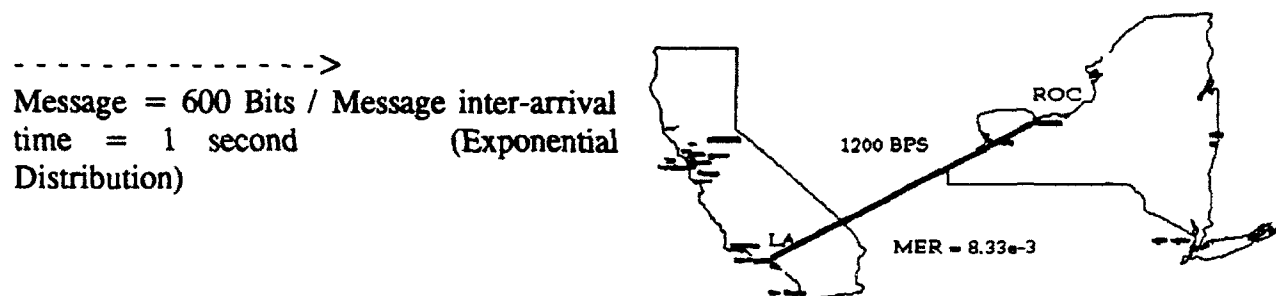
Figure 4.2.2-1

Parameter/Result	INS	COMNET II.5
Source	ROC	ROC
Destination	LA	LA
Message Size (bits)	600	600
Message Generation Rate	1	1 (per second - exp. distribution)
Message Error Rate (Msgs/Sec)	3.833e-3	3.833e-3
Average Message Delay (ms)	506	719

In the case of COMNET II.5, the message inter-arrival times can be specified to follow an exponential distribution, which is consistent with the M/M/1 queuing model implementation of INS. The service or processing rates of the given links in COMNET II.5 cannot be specified to follow a particular distribution. INS, again following the M/M/1 queuing model, considers nodal service rates to follow an exponential distribution. Additionally, COMNET II.5 sums the average time spent in the outgoing transmit queue with the time required to transmit the message. This process is repeated for every outgoing port, as there is a queue/server pair for each, and the results are averaged. INS sums the time required to transmit the average number of messages in the queue with the time required to transmit a message for a single queue/server pair that represents a composite of the outgoing links. Therefore, it is unlikely that resulting delay values will be the same.

It is important to note why the previous paragraph discusses link servicing in the case of COMNET II.5 and node servicing for INS. COMNET II.5 allows node servicing rates to be specified, but as was discussed earlier, the specification of these rates introduces another queue and servicing agent. Whenever a link is specified in COMNET II.5, an outgoing port with a queue and servicing agent is introduced into the model. Therefore, specifying node servicing rates results in two queue/servicing agent combinations for a single source node. INS, on the other hand, considers a node to contain only a single queue and a single servicing agent. Nodal servicing rates were not specified in COMNET II.5 in order to promote consistency with the INS implementation.

Although it would have been gratifying to correlate resulting delay values, that is not the primary purpose of a network simulator such as INS. More important is the ability to simulate a network topology quickly and easily, and to be able to compare the relative merits of differing topologies. The network simulator should demonstrate the effects of topology changes in the form of relative performance improvements or degradation. The more important "sanity" check is the comparison of path selection and message allocation.

4.4.2.2 Path Selection and Message Allocation

The network shown in Figure 5.2.2-1 has exactly five paths, assuming that no nodes are to be revisited, from source node 1A to destination node 5A. INS determines the five best paths for a given source-destination pair and allocates messages over three of those five paths depending on which satisfy best the chosen quality goal. As can be seen in Appendix B, the actual results files for the simulation of the network represented in Figure 5.2.2-1 and Table 5.2.2-1, the five available paths were found by INS and are listed in the order from best to worst based on a quality goal of low delay.
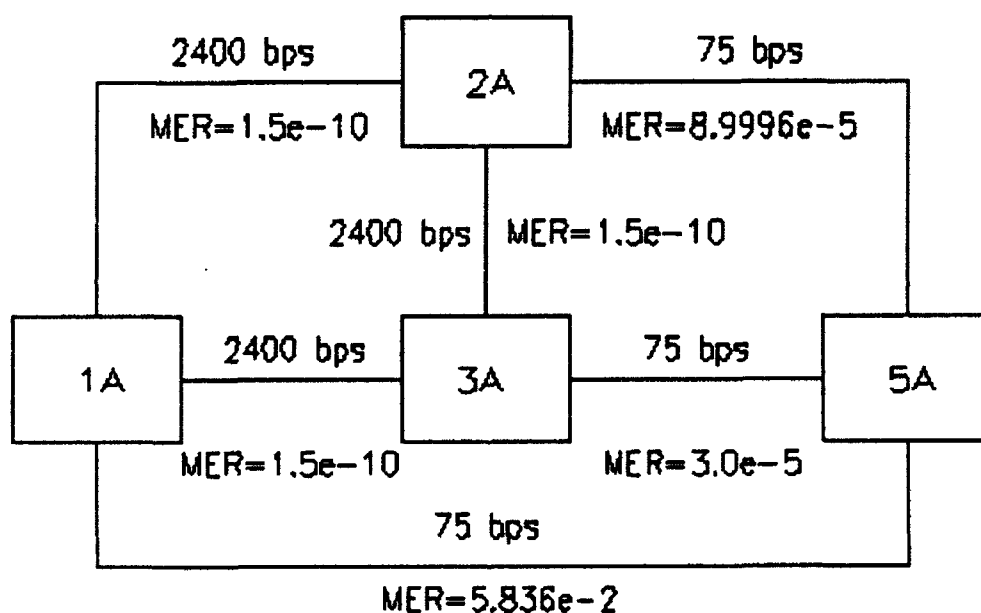
Message = 150 Bits / Message inter-arrival time
= 0.6667 seconds
(Exponential Distribution)

Figure 4.4.2-2

Parameter/Result	INS	COMNET II.5
Source	1A	1A
Destination	5A	5A
Message Size (Bits)	150	150
Message Inter-arrival time	0.6667	0.6667 (seconds - exp dist)
Messages 1A to 2A link (% of total)	33%	33%
Messages 1A to 3A link	33%	33%
Messages 1A to 5A link	0%	0%
Messages 3A to 2A link	0%	0%
Messages 2A to 5A link	33%	32%
Messages 3A to 5A link	33%	32%
Throughput (BPS)	207.65	208.16

Table 4.4.2-2

Since INS determines the five best paths and allocates messages over three of those paths, INS implements a form of circuit switching. Although COMNET II.5 allows the user to simulate a circuit switched network, it is more informative to simulate a packet switched network and view the results to determine if the developed paths and path loading corresponds to INS' results.

As can be seen in INS results and COMNET II.5 results in Table 4.4.2-2, with the exception of COMNET II.5 routing messages between nodes 2A and 3A, the paths selected by each were almost identical. Additionally, the resulting message allocation is intuitively correct when examining the network topology and link characteristics. It is clear that for the message transmission rate specified, the message allocation should be approximately equal over the three chosen paths.

Also note that INS and COMNET II.5 predict the same network throughput. In the case of INS, actual network throughput is presented as network termination rate. COMNET II.5's throughput result represents actual network throughput. When there is no message loss occurring in the network simulations, both simulators reported identical throughput results as throughput equals the source rate. More important are the results shown in Table 4.4.2-2, as they demonstrate that

when message loss is occurring or the network topology is stressed, both simulators report almost identical throughput results as an indication of the network topologies maximum throughput potential.

4.4.3 CACI/INS Benchmark Conclusion

Although the networks simulated were very simple networks, the results provide for an important "sanity" check. The networks used allow an observer to intuitively determine ideal network topologies therefore removing the requirement that either network simulator be considered the "right" simulator. Both simulators provided correlative results, with the exception of delay values, while at the same time agreeing with what could be considered intuitively obvious.

The network topology shown in Figure 4.4.2-2 was chosen to promote message allocation, messages divided equally amongst the three chosen paths, corresponding to message allocations supported by INS. Although this tailoring was biased, INS demonstrated that it does select the topology it was designed to select. Additional testing and investigation could be pursued to determine if additional message allocations should be simulated, different path quality measurements should be used, and different network results metrics developed. INS provides the foundation, through generally easy source code modifications, to investigate these types of changes.

This study of the network simulators and their associated results indicates that the simulators are complementary rather than concluding that a simulator has a clear advantage. INS offers a method for determining node-to-node link characteristics through the use of integrated IONCAP and Modem BER tables. INS also allows for rapid prototyping of network topologies as it is analytical and relatively fast when compared to CACI's discrete event simulation. CACI, once configured based on link characteristics developed in INS, provides for a more thorough, albeit longer, simulations due to the ability to more thoroughly introduce network overhead effects, such as retry algorithms, and less restrictive message allocation. Together they form a formidable simulation tool.

5.0 Summary

The IHFDN project has investigated networking issues and techniques for a 100 member HF network, spread over 8000 miles. Techniques have been developed which take into account frequency hopping, communications security (COMSEC), low probability of detection and exploitation (LPD/LPE), MIL-STD-188-110 modems, and integrated link quality analysis (LQA) and data.

Section 1 of this final report summarized the characteristics of HF communication which impact the design of all HF networks, including the IHFDN. Network design is shaped by the HF environment, link quality analysis (LQA), tailoring of established networking techniques, and LPE/LPD waveforms.

Section 2 established a point of departure (POD) for the IHFDN, which was based on a foundation of previous developments in networking theory, LQA, modem technology, frequency hopping, COMSEC, and the open systems interconnect (OSI) model.

Section 3 covered concept studies which proved that new, key IHFDN technologies could be implemented even with present day products and methods. The first concept study dealt with prediction of HF conditions. Specific situations of HF channel propagation are unpredictable, yet the extremes of usable HF channel propagation can be predicted with IONCAP or even very simple spread sheet methods. These HF propagation extremes are valuable boundary conditions for network evaluation, which are even more meaningful test scenarios than individual day to day test cases.

The second and third concept studies proved that it is possible to extract accurate, real time LQA and BER data from received MIL-STD-188-110A data, without the need for test patterns or sounding signals.

The fourth concept study measured the message delivery time and channel utilization for carrier sense multiple access (CSMA) methods, considering various levels of collision sensing. The effectiveness of collision sensing is typically poor in HF systems due to half duplex operation, and the hidden terminal problem. CSMA proves to be a simple, but inefficient access method in situations with ineffective collision sensing methods.

Section 4 describes the Improved HF Data Network Simulator (INS) which was created to test and demonstrate the IHFDN techniques. This PC based, user friendly simulation employs numerical, closed form techniques to quickly and accurately determine network throughput, delay, and reliability for a user defined network. The INS was bench marked and compared

with the commercially available CACI COMNET II.5 simulation, which is also a deliverable of this project.

The next step beyond the IHFDN project should be the application and evaluation of IHFDN techniques for a real world HF network. Network nodes should be developed and deployed, which embody the core aspects of the IHFDN design:

- Nodes which are fully interactive, without the need for a net controller or gateways.

- Geographic diversity which requires a variety of communications over NVIS and oblique skywave paths.

- State-of-the-art modems for robust performance, OPSEC, and integrated LQA techniques, namely MIL-STD-188-110/FED-STD-1052.

- Frequency agile radios which can quickly perform link establishment and channel evaluation (for example, hop rates of on the order of 20 hops per second).

- PC based control for message entry, message handling, channel quality statistics collection, and propagation prediction using IONCAP and the IHFDN spreadsheet (for comparison purposes).

- State of the art ARQ, selective call, and automatic bit rate adjustment for the data link layer, namely FED-STD-1052\MIL-STD-188-110A.

- Automatic channel evaluation and channel change in the event of HF channel degradation, without operator intervention.

Deployment and evaluation of this network would allow the IHFDN techniques to be proven and refined, and fed back into the INS to improve the accuracy of its simulation results.

APPENDIX A - SIMULATION RESULTS

APPENDIX A - Simulation Results for Network Described in Figure 4.4.2-1 and Table 4.4.2-1.

```
-----------------------------------------------------------------------
                                   INS
-----------------------------------------------------------------------
File - TEST1.NET

/************************************************/
NETWORK DATA
/************************************************/
name: TEST
quality_goal: low_delay
number_nodes: 15
number_nets: 10
num_nodes_in_net 1: 1
num_nodes_in_net 2: 0
num_nodes_in_net 3: 1
num_nodes_in_net 4: 0
num_nodes_in_net 5: 0
num_nodes_in_net 6: 0
num_nodes_in_net 7: 0
num_nodes_in_net 8: 0
num_nodes_in_net 9: 0
num_nodes_in_net 10: 0
channel_type: good
channel_rank: 1st
lqa: high
lqa_uncertainty: 0
traffic_length: 600
ack_length: 10
arrival_rate: 100
ssn_month: jan_10
tx_reduction: 0
noise_increase: 0
inter_link_delay: 0
intra_link_delay: 0
/************************************************/
NODE DATA
/************************************************/
name: Roc
index: 0
net: 1
latitude_degrees: 43
latitude_direction: north
vertical_coordinate: 76
longitude_degrees: 78
longitude_direction: west
horizontal_coordinate: 146
generation_rate: 3600
bit_rate: 2400
tx_reduction: 0
noise_increase: 0
number_dests: 1
```

```
source_index: 0
DESTINATIONS
LA     index: 2     percent: 100
^^^
/**************************************************/
```

```
name: LA
index: 2
net: 3
latitude_degrees: 34
latitude_direction: north
vertical_coordinate: 95
longitude_degrees: 119
longitude_direction: west
horizontal_coordinate: 50
generation_rate: 1000
bit_rate: 2400
tx_reduction: 0
noise_increase: 0
number_dests: 0
source_index: EMPTY
DESTINATIONS
^^^
/**************************************************/


File - NODE.TXT

Roc, Roc : Distance = 0, Msgs_per_hr = 0.0000e+000
Roc, LA : Distance = 2277, Msgs_per_hr = 3.6000e+003
LA, Roc : Distance = 2277, Msgs_per_hr = 0.0000e+000
LA, LA : Distance = 0, Msgs_per_hr = 0.0000e+000


File - TIME_2.TXT

Roc, Roc : Bit_rate = 2400, Network_snr = 31, MER = 5.9999e-010;
Roc, LA : Bit_rate = 1200, Network_snr = 12, MER = 3.8326e-003;
LA, Roc : Bit_rate = 1200, Network_snr = 12, MER = 3.8326e-003;
LA, LA : Bit_rate = 2400, Network_snr = 31, MER = 5.9999e-010;


File - PATHS_2.TXT

source_name : Roc
source_index : 0
destination : LA
destination_index : 2
path : Roc, LA
lo_lqa_cost = 1.000000
msg_flow = 3600.000000
^^^
/******************************/
```

```
File - TRAF_2.TXT

Traffic_flows Roc, Roc : 0.0000e+000
Traffic_flows Roc, LA : 3.6000e+003
Traffic_flows LA, Roc : 0.0000e+000
Traffic_flows LA, LA : 0.0000e+000


File - NODE_2.TXT

Node : Roc
Inflow_rate : 0.0000e+000
Outflow_rate : 6.0000e+002
Inter_net_outflow : 6.0000e+002
Intra_net_outflow : 0.0000e+000
Source_rate : 6.0000e+002
Termination_rate : 0.0000e+000
Throughput : 6.0000e+002
Composite_bit_rate : 1.2000e+003
Error_rate : 3.8326e-003
Missed_msg_ratio : 1.0038e+000
Adjusted_length : 6.0231e+002
Service_demand : 6.0231e+002
Intensity : 5.0192e-001
Linking_delay : 0.0000e+000
Delay : 5.0580e-001
TX data loss : 0.0000e+000
/**************************************************/
Node : LA
Inflow_rate : 6.0000e+002
Outflow_rate : 0.0000e+000
Inter_net_outflow : 0.0000e+000
Intra_net_outflow : 0.0000e+000
Source_rate : 0.0000e+000
Termination_rate : 6.0000e+002
Throughput : 6.0000e+002
Composite_bit_rate : 2.4000e+003
Error_rate : 0.0000e+000
Missed_msg_ratio : 1.0000e+000
Adjusted_length : 6.1000e+002
Service_demand : 0.0000e+000
Intensity : 0.0000e+000
Linking_delay : 0.0000e+000
De_ay : 0.0000e+000
TX data loss : 0.0000e+000
/**************************************************/
```

```
File - PATH_2.TXT

Source : Roc
Destination : LA
Delay = 5.0580e-001
TX Data loss = 0.0000e+000
Available bandwidth = 5.9769e+002
LPE/LPD = 1.2000e+001
/***********************************/


File - NET_2.TXT

Network name : TEST1
Random_seed : 1
Path combination : 123
Allocation method = A
Source_rate = 6.0000e+002
Termination_rate = 6.0000e+002
Reliability = 1.0000e+000
Avg_delay = 5.0580e-001
Available bandwidth = 5.9769e+002
LPE/LPD = 1.2000e+001
```

```
------------------------------------------------------------------------
                        CACI - COMNET II.5
------------------------------------------------------------------------
CACI COMNET II.5  RELEASE 4.02      09/11/1991      19:39:16      PAGE   1

                    TEST1

                NODE ATTRIBUTES

NODE ID CODE             LA                ROC

NODE NAME                Los       Rochester
                         Angeles


SWITCHING TIMES (MS)
   CALL SETUP TIME       0.         0.
   V CKT SETUP PKT TIME        0.   0.
   PKT PROCESSING TIME   0.         0.
   PKT PROC TM PER KBYTE       0.   0.
BUFFER SIZE (BYTES)      no limit    no limit
MSG-CUTOFF (BYTES)       buff. size  buff. size
PKT SWITCH PROCESSORS    1          1
PACKETIZING DELAY (MS)        0.    0.

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                    TEST1

          POINT-TO-POINT LINK GROUP ATTRIBUTES

LINK GROUP ID CODE        ROC_TO_LA

NODE ENDPOINT 1 ID CODE   LA
NODE ENDPOINT 2 ID CODE   ROC
NUMBER OF CIRCUITS        1
CIRCUIT-SWITCHING ATTRIBUTES
   BANDWIDTH ALLOCATION?  yes
   C.S. SIG. TIME (MS)    0.
   CALL ACCESS LEVEL      1
   QUEUEING ALLOWED?      no
   CALL QUEUE LIMIT       none
PACKET-SWITCHING ATTRIBUTES
   TRANS. RATE (KBPS)     1.20
   FRAME OH BYTES         0
   MIN FRAME BYTES        0
   MAX FRAME BYTES        0
   FRAME ERROR PROB       .003833000
   FRAME ASSEMBLY         no
   FDX RETURN LNK GROUP
   PROPAGA. DELAY (MS)    0.
   MAX BF USE (BYTES)     no limit
   BUF RESRV (BYTES)      0
```

```
    BUFF. REL. TIME (MS)          0.
    NO. TRANS. Q's               1
    MIN PRIORITY--Q 1            1
    MX Q-SVC-TM (MS)--Q 1         0.
    MAX VIRT. CKTS   no limit
FAILURE ATTRIBUTES
    TIME-TO-FAILURE (MIN)
    PROB. DISTRIBUTION     unspecified
    PARAMETER 1              0.
    PARAMETER 2              0.
    PARAMETER 3              0.
    PARAMETER 4              0.
    STREAM                  0
    TIME-TO-REPAIR (MIN)
    PROB. DISTRIBUTION     unspecified
    PARAMETER 1              0.
    PARAMETER 2              0.
    PARAMETER 3              0.
    PARAMETER 4              0.
    STREAM                  0
```

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TEST1

CLASS-OF-SERVICE ATTRIBUTES

```
CLASS-OF-SERVICE ID CODE       _01
PRIORITY                  1
MAX HOP COUNT             3
CIRCUIT-SWITCHING ATTRIBUTES
    CALL RETRY TIME (MIN)
    PROB. DISTRIBUTION     unspecified
    PARAMETER 1              0.
    PARAMETER 2              0.
    PARAMETER 3              0.
    PARAMETER 4              0.
    STREAM                  0
    BANDWIDTH REQT (KBPS)       0.
PACKET-SWITCHING ATTRIBUTES
    PKT. SIZE (BYTES)          75
    PKT. OH (BYTES)       0
    BLOCK DROPPING?      no
```

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TEST1
DATA MESSAGE ATTRIBUTES

TRAFFIC SCALING FACTOR = 1.00

```
ORIGIN NODE ID CODE          ROC
DEST. NODE ID CODE           LA
```

```
CLASS-OF-SVC ID CODE              _01
WINDOW SIZE                    0
MSG INTERARRIVAL TIME  (SEC)
   PROB. DISTRIBUTION      exponential
   PARAMETER 1            1.0000
   PARAMETER 2            0.
   PARAMETER 3            0.
   PARAMETER 4            0.
   STREAM                 1
MSG SIZE
   UNITS                 packets
   PROB. DISTRIBUTION         constant
   PARAMETER 1           1.0000
   PARAMETER 2           0.
   STREAM                0
TRIGGERED MSG DEST
TRIGGERED MSG COS
TRIG. MSG DELAY  (SEC)             0.
```

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               TEST1

CIRCUIT-SWITCHING OPERATION

```
Call Preemption Enabled?           No
Call Routing Strategy              Source-Node
```

PACKET-SWITCHING OPERATION

```
Message Traffic Switching          Packet-Switched
Acknowledgement Packet Size        0
Control Packet Priority            0        (0 defaults to highest priority)
Acknowledge End of Message         No
Retransmit Interval             500       millisec
Routing Update Interval       10000       millisec
Dropped-Block Size                 0       bytes
Block Dropping Thresholds          Undefined
Packet Routing Strategy            Shortest Path w/ Delay Metric
Alternate Routing Rule             Minimum Link Queue Size
Traffic Measure Type               End-to-End Delay
Max Distance Change Threshold      0       millisec
Distance Change Threshold Reduction     0   millisec
Max Flooded Packet Life            0.  sec
Virtual Call Retry Interval       60.00 sec
Max Retransmit Attempts            0
Call Request Packet Size (Bytes)      0
Call Connect Packet Size (Bytes)      0
Virtual Call Flow Control Strategy     Undefined
```

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               TEST1

ROUTING COSTS FOR CONGESTION LEVEL 1

```
CIRCUIT        COS
  GROUP        _01

ROC_TO_LA      1
```

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TEST1

CIRCUIT GROUP PERFORMANCE
FOR
PACKET-SWITCHED TRAFFIC
FROM   0. TO   60. MINUTES

```
CIRCUIT GROUP ID CODE     ROC_TO_LA
TRANSMITTING NODE
NUMBER OF CIRCUITS            1
BANDWIDTH LIMIT (KBPS)        1.20
BANDWIDTH USED (KBPS)
  AVERAGE               .59
  STANDARD DEVIATION         .60
  MAXIMUM              1.20
CIRCUIT GROUP UTIL %          49.44

FRAMES SENT          3550
FRAMES RESENT          11
PACKETS SENT         3550
PACKET QUEUE TIME (MS)
  AVERAGE            217.78
  STANDARD DEVIATION       334.79
  MAXIMUM           2499.76
```

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TEST1

TRANSMISSION QUEUE STATISTICS
FROM   0. TO   60. MINUTES

```
NODE ID CODE          LA              ROC
CIRCUIT GROUP ID CODE    ROC_TO_LA    ROC_TO_LA
MIN QUEUE PRIORITY        1            1

PACKETS TRANSMITTED          0          3550
PACKET QUEUE TIME (MS)
  AVERAGE            0.217.78
  MAXIMUM            02499.76
```

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                    TEST1

                    PACKET SWITCHING
                NODE UTILIZATION STATISTICS
                 FROM   0. TO   60. MINUTES

NODE   Los   Rochester
                  Angeles

BUFFER USE (BYTES)
   AVERAGE   0. 53.19
   STANDARD DEVIATION   0. 65.95
   MAXIMUM   0.450.00

PACKETS PROCESSED   3549   3551
PACKETS BLOCKED   0   0

PKT SWITCH WAIT TIME (MS)
   AVERAGE   0. 0.
   STANDARD DEVIATION   0. 0.
   MAXIMUM   0. 0.

PROCESSOR UTILIZATION
   PROCESSORS PER NODE   1   1
   AVG BUSY PROCESSORS   0. 0.
   UTILIZATION %   0. 0.

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                    TEST1

                  BUFFER UTILIZATION
                        BY
                  OUTGOING PORT
           FROM   0. TO   60. MINUTES

NODE ID CODE   LA   ROC

CIRCUIT GROUP ID CODE   ROC_TO_LA   ROC_TO_LA

BUFFER USE (BYTES)
   AVERAGE   0. 53.19
   STANDARD DEVIATION   0. 65.95
   MAXIMUM   0.450.00

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TEST1

MESSAGE DELAY STATISTICS
FROM   0. TO   60. MINUTES

ORIGIN	DEST.	COS	MSGS BLOCKED	MSGS SENT AND RECEIVED	AVG MESSAGE SIZE IN BYTES	DELAY (SECONDS) AVERAGE	DELAY (SECONDS) MAXIMUM	% ABOVE 0.	AVG TOTAL SECONDS	DELAY PACKETS	(MS)
ROC	LA	_01	0	3549	75.0	.72	3.00	100.00	3549	719	
NETWORK TOTALS			0	3549	75.0	.72	3.00	100.00	3549	719	

NETWORK THROUGHPUT: .6 KILOBITS PER SECOND

APPENDIX B - SIMULATION RESULTS

APPENDIX B - Simulation Results for Network Described in Figure 4.4.2-2 and Table 4.4.2-2.

```
-----------------------------------------------------------------------
                                  INS
-----------------------------------------------------------------------


File - TEST2B2.NET

/************************************************/
NETWORK DATA
/************************************************/
name: TEST2B2
quality_goal: high_throughput
number_nodes: 7
number_nets: 5
num_nodes_in_net 1: 1
num_nodes_in_net 2: 1
num_nodes_in_net 3: 1
num_nodes_in_net 4: 0
num_nodes_in_net 5: 1
channel_type: good
channel_rank: 1st
lqa: high
lqa_uncertainty: 0
traffic_length: 150
ack_length: 1
arrival_rate: 100
ssn_month: jan_10
tx_reduction: 0
noise_increase: 0
inter_link_delay: 0
intra_link_delay: 0
/************************************************/
NODE DATA
/************************************************/
name: 1A
index: 0
net: 1
latitude_degrees: 0
latitude_direction: north
vertical_coordinate: 171
longitude_degrees: 30
longitude_direction: west
horizontal_coordinate: 218
generation_rate: 5400
bit_rate: 2400
tx_reduction: 0
noise_increase: 0
number_dests: 1
source_index: 0
DESTINATIONS
5A     index: 6      percent: 100
```

```
^^^
/*************************************************/
name: 2A
index: 1
net: 2
latitude_degrees: 0
latitude_direction: north
vertical_coordinate: 171
longitude_degrees: 20
longitude_direction: west
horizontal_coordinate: 239
generation_rate: 1000
bit_rate: 2400
tx_reduction: 0
noise_increase: 0
number_dests: 0
source_index: EMPTY
DESTINATIONS
^^^
/*************************************************/
name: 3A
index: 2
net: 3
latitude_degrees: 30
latitude_direction: north
vertical_coordinate: 104
longitude_degrees: 10
longitude_direction: west
horizontal_coordinate: 262
generation_rate: 1000
bit_rate: 2400
tx_reduction: 0
noise_increase: 0
number_dests: 0
source_index: EMPTY
DESTINATIONS
^^^
/*************************************************/
name: 5A
index: 6
net: 5
latitude_degrees: 0
latitude_direction: north
vertical_coordinate: 171
longitude_degrees: 65
longitude_direction: east
horizontal_coordinate: 430
generation_rate: 1000
bit_rate: 75
tx_reduction: 0
noise_increase: 0
number_dests: 0
source_index: EMPTY
DESTINATIONS
^^^
/*************************************************/
```

```
File - TIME_2.TXT

1A, 1A : Bit_rate = 2400, Network_snr = 31, MER = 1.5000e-010;
1A, 2A : Bit_rate = 2400, Network_snr = 29, MER = 1.5000e-010;
1A, 3A : Bit_rate = 2400, Network_snr = 32, MER = 1.5000e-010;
1A, 5A : Bit_rate = 75, Network_snr = -1, MER = 5.8360e-002;
2A, 1A : Bit_rate = 2400, Network_snr = 29, MER = 1.5000e-010;
2A, 2A : Bit_rate = 2400, Network_snr = 31, MER = 1.5000e-010;
2A, 3A : Bit_rate = 2400, Network_snr = 30, MER = 1.5000e-010;
2A, 5A : Bit_rate = 75, Network_snr = 2, MER = 8.9996e-005;
3A, 1A : Bit_rate = 2400, Network_snr = 32, MER = 1.5000e-010;
3A, 2A : Bit_rate = 2400, Network_snr = 30, MER = 1.5000e-010;
3A, 3A : Bit_rate = 2400, Network_snr = 31, MER = 1.5000e-010;
3A, 5A : Bit_rate = 75, Network_snr = 4, MER = 3.0000e-005;
5A, 1A : Bit_rate = 75, Network_snr = -1, MER = 5.8360e-002;
5A, 2A : Bit_rate = 75, Network_snr = 2, MER = 8.9996e-005;
5A, 3A : Bit_rate = 75, Network_snr = 4, MER = 3.0000e-005;
5A, 5A : Bit_rate = 75, Network_snr = 31, MER = 0.0000e+000;

File PATHS_2.TXT   source_name : 1A
source_index : 0
destination : 5A
destination_index : 6
path : 1A, 5A
lo_lqa_cost = 0.000152
msg_flow = 1800.000000
^^^
path : 1A, 2A, 5A
lo_lqa_cost = 0.000341
msg_flow = 1800.000000
^^^
path : 1A, 3A, 5A
lo_lqa_cost = 0.000376
msg_flow = 1800.000000
^^^
path : 1A, 3A, 2A, 5A
lo_lqa_cost = 0.000511
msg_flow = 0.000000
^^^
path : 1A, 2A, 3A, 5A
lo_lqa_cost = 0.000564
msg_flow = 0.000000
^^^
/******************************/
```

File - TRAF_2.TXT

```
Traffic_flows 1A,.1A : 0.0000e+000
Traffic_flows 1A, 2A : 1.8000e+003
Traffic_flows 1A, 3A : 1.8000e+003
Traffic_flows 1A, 5A : 1.8000e+003
Traffic_flows 2A, 1A : 0.0000e+000
Traffic_flows 2A, 2A : 0.0000e+000
Traffic_flows 2A, 3A : 0.0000e+000
Traffic_flows 2A, 5A : 1.8000e+003
Traffic_flows 3A, 1A : 0.0000e+000
Traffic_flows 3A, 2A : 0.0000e+000
Traffic_flows 3A, 3A : 0.0000e+000
Traffic_flows 3A, 5A : 1.8000e+003
Traffic_flows 5A, 1A : 0.0000e+000
Traffic_flows 5A, 2A : 0.0000e+000
Traffic_flows 5A, 3A : 0.0000e+000
Traffic_flows 5A, 5A : 0.0000e+000
   File = NODE_2.TXT
```

```
Node : 1A
Inflow_rate : 0.0000e+000
Outflow_rate : 2.2500e+002
Inter_net_outflow : 2.2500e+002
Intra_net_outflow : 0.0000e+000
Source_rate : 2.2500e+002
Termination_rate : 0.0000e+000
Throughput : 2.2500e+002
Ccmposite_bit_rate : 2.1176e+002
Error_rate : 1.9453e-002
Missed_msg_ratio : 1.0198e+000
Adjusted_length : 1.5298e+002
Service_demand : 2.2946e+002
Intensity : 1.0836e+000
Linking_delay : 0.0000e+000
Delay : 9.9999e+037
TX data loss : 1.7355e+001
/**************************************************/
Node : 2A
Inflow_rate : 7.5000e+001
Outflow_rate : 7.5000e+001
Inter_net_outflow : 7.5000e+001
Intra_net_outflow : 0.0000e+000
Source_rate : 0.0000e+000
Termination_rate : 0.0000e+000
Throughput : 7.5000e+001
Composite_bit_rate : 7.5000e+001
Error_rate : 8.9996e-005
Missed_msg_ratio : 1.0001e+000
Adjusted_length : 1.5101e+002
Service_demand : 7.5507e+001
```

```
Intensity : 1.0068e+000
Linking_delay : 0.0000e+000
Delay : 9.9999e+037
TX data loss : 5.0335e-001
/*************************************************/
Node : 3A
Inflow_rate : 7.5000e+001
Outflow_rate : 7.5000e+001
Inter_net_outflow : 7.5000e+001
Intra_net_outflow : 0.0000e+000
Source_rate : 0.0000e+000
Termination_rate : 0.0000e+000
Throughput : 7.5000e+001
Composite_bit_rate : 7.5000e+001
Error_rate : 3.0000e-005
Missed_msg_ratio : 1.0000e+000
Adjusted_length : 1.5100e+002
Service_demand : 7.5502e+001
Intensity : 1.0067e+000
Linking_delay : 0.0000e+000
Delay : 9.9999e+037
TX data loss : 4.9891e-001
/*************************************************/
Node : 5A
Inflow_rate : 2.2500e+002
Outflow_rate : 0.0000e+000
Inter_net_outflow : 0.0000e+000
Intra_net_outflow : 0.0000e+000
Source_rate : 0.0000e+000
Termination_rate : 2.0765e+002
Throughput : 2.2500e+002
Composite_bit_rate : 7.5000e+001
Error_rate : 0.0000e+000
Missed_msg_ratio : 1.0000e+000
Adjusted_length : 1.5100e+002
Service_demand : 0.0000e+000
Intensity : 0.0000e+000
Linking_delay : 0.0000e+000
Delay : 0.0000e+000
TX data loss : 0.0000e+000
/*************************************************/
   File - PATH_2.TXT

Source : 1A
Destination : 5A
Delay = 9.9999e+037
TX Data loss = 1.7355e+001
Available bandwidth = -1.7699e+001
LPE/LPD = 1.0833e+001
/************************************/
```

```
File - NET_2.TXT
 Network name : TEST2B2
Random_seed : 1
Path combination : 123
Allocation method = A
Source_rate = 2.2500e+002
Termination_rate = 2.0765e+002
Reliability = 9.2287e-001
Avg_delay = 9.9999e+037
Available bandwidth = -1.7699e+001
LPE/LPD = 1.0833e+001
```

```
------------------------------------------------------------------------
                          CACI - COMNET II.5
------------------------------------------------------------------------
```

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TEST2B

NODE ATTRIBUTES

NODE ID CODE	1A	2A	3A	5A
NODE NAME	1A	2A	3A	5A

SWITCHING TIMES (MS)

CALL SETUP TIME	0. 0.	0.	0.	
V CKT SETUP PKT TIME	0.	0.	0.	0.
PKT PROCESSING TIME	0.	0.	0.	0.
PKT PROC TM PER KBYTE	0.	0.	0.	0.
BUFFER SIZE (BYTES)	no limit	no limit	no limit	no limit
MSG-CUTOFF (BYTES)	buff. size	buff. size	buff. size	buff. size
PKT SWITCH PROCESSORS	1	1	1	1
PACKETIZING DELAY (MS)	0.	0.	0.	0.

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TEST2B

POINT-TO-POINT LINK GROUP ATTRIBUTES

LINK GROUP ID CODE	1A-2A	1A-2A	1A-3A	1A-3A
NODE ENDPOINT 1 ID CODE	1A	2A	1A	3A
NODE ENDPOINT 2 ID CODE	2A	1A	3A	1A
NUMBER OF CIRCUITS	1	1	1	1

CIRCUIT-SWITCHING ATTRIBUTES

BANDWIDTH ALLOCATION?	yes	yes	yes	yes
C.S. SIG. TIME (MS)	0. 0.	0.	0.	
CALL ACCESS LEVEL	1	1	1	1
QUEUEING ALLOWED?	no	no	no	no
CALL QUEUE LIMIT	none	none	none	none

PACKET-SWITCHING ATTRIBUTES

TRANS. RATE (KBPS)	2.40	2.40	2.40	2.40
FRAME OH BYTES	0	0	0	0
MIN FRAME BYTES	0	0	0	0
MAX FRAME BYTES	0	0	0	0
FRAME ERROR PROB	0.	0.	0.	0.
FRAME ASSEMBLY	no	no	no	no
FDX RETURN LNK GROUP	1A-2A	1A-2A	1A-3A	1A-3A
PROPAGA. DELAY (MS)	0. 0.	0.	0.	
MAX BF USE (BYTES)	no limit	no limit	no limit	no limit
BUF RESRV (BYTES)	0	0	0	0

```
BUFF. REL. TIME (MS)           0.  0.        0.         0.
NO. TRANS. Q's           1            1      1          1
MIN PRIORITY--Q 1        1            1      1          1
MX Q-SVC-TM (MS)--Q 1    0.  0.       0.        0.
MAX VIRT. CKTS  no limit    no limit   no limit    no limit
FAILURE ATTRIBUTES
  TIME-TO-FAILURE (MIN)
  PROB. DISTRIBUTION     unspecified unspecified unspecified unspecified
  PARAMETER 1            0.  0.       0.         0.
  PARAMETER 2            0.  0.       0.         0.
  PARAMETER 3            0.  0.       0.         0.
  PARAMETER 4            0.  0.       0.         0.
  STREAM                 0            0      0          0
  TIME-TO-REPAIR (MIN)
  PROB. DISTRIBUTION     unspecified unspecified unspecified unspecified
  PARAMETER 1            0.  0.       0.         0.
  PARAMETER 2            0.  0.       0.         0.
  PARAMETER 3            0.  0.       0.         0.
  PARAMETER 4            0.  0.       0.         0.
  STREAM                 0            0      0          0

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                      TEST2B
              POINT-TO-POINT LINK GROUP ATTRIBUTES

LINK GROUP ID CODE        1A-5A         1A-5A        2A-3A        2A-3A

NODE ENDPOINT 1 ID CODE    1A            5A           2A      3A
NODE ENDPOINT 2 ID CODE    5A            1A           3A      2A
NUMBER OF CIRCUITS          1            1      1          1
CIRCUIT-SWITCHING ATTRIBUTES
  BANDWIDTH ALLOCATION?    yes          yes          yes      yes
  C.S. SIG. TIME (MS)      0.  0.       0.         0.
  CALL ACCESS LEVEL        1            1      1          1
  QUEUEING ALLOWED?        no           no     no         no
  CALL QUEUE LIMIT        none          none         none     none
PACKET-SWITCHING ATTRIBUTES
  TRANS. RATE (KBPS)           .072.40   2.40      2.40
  FRAME OH BYTES         0            0      0          0
  MIN FRAME BYTES        0            0      0          0
  MAX FRAME BYTES        0            0      0          0
  FRAME ERROR PROB    .058359999   .058359999 0.      0.
  FRAME ASSEMBLY         no           no     no         no
  FDX RETURN LNK GROUP   1A-5A         1A-5A        2A-3A        2A-3A
  PROPAGA. DELAY (MS)       0.  0.       0.         0.
  MAX BF USE (BYTES)    no limit    no limit   no limit    no limit
  BUF RESRV (BYTES)        0            0      0          0
  BUFF. REL. TIME (MS)     0.  0.       0.         0.
  NO. TRANS. Q's           1            1      1          1
  MIN PRIORITY--Q 1        1            1      1          1
  MX Q-SVC-TM (MS)--Q 1    0.  0.       0.        0.
  MAX VIRT. CKTS  no limit    no limit   no limit    no limit
```

```
FAILURE ATTRIBUTES
  TIME-TO-FAILURE (MIN)
  PROB. DISTRIBUTION     unspecified unspecified unspecified unspecified
  PARAMETER 1            0.  0.       0.       0.
  PARAMETER 2            0.  0.       0.       0.
  PARAMETER 3            0.  0.       0.       0.
  PARAMETER 4            0.  0.       0.       0.
  STREAM                 0            0    0        0
  TIME-TO-REPAIR (MIN)
  PROB. DISTRIBUTION     unspecified unspecified unspecified unspecified
  PARAMETER 1            0.  0.       0.       0.
  PARAMETER 2            0.  0.       0.       0.
  PARAMETER 3            0.  0.       0.       0.
  PARAMETER 4            0.  0.       0.       0.
  STREAM                 0            0    0        0
```

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                         TEST2B
              POINT-TO-POINT LINK GROUP ATTRIBUTES

```
LINK GROUP ID CODE      2A-5A          2A-5A        3A-5A        3A-5A

NODE ENDPOINT 1 ID CODE   2A             5A            3A    5A
NODE ENDPOINT 2 ID CODE   5A             2A            5A    3A
NUMBER OF CIRCUITS        1              1     1        1
CIRCUIT-SWITCHING ATTRIBUTES
  BANDWIDTH ALLOCATION?   yes            yes           yes    yes
  C.S. SIG. TIME (MS)     0.  0.         0.        0.
  CALL ACCESS LEVEL       1              1     1        1
  QUEUEING ALLOWED?       no             no    no       no
  CALL QUEUE LIMIT        none           none          none   none
PACKET-SWITCHING ATTRIBUTES
  TRANS. RATE (KBPS)           .072.40      .07    2.40
  FRAME OH BYTES         0              0     0        0
  MIN FRAME BYTES        0              0     0        0
  MAX FRAME BYTES        0              0     0        0
  FRAME ERROR PROB   .000090000   .000090000  .000030000  .000030000
  FRAME ASSEMBLY        no             no    no       no
  FDX RETURN LNK GROUP  2A-5A          2A-5A         3A-5A        3A-5A
  PROPAGA. DELAY (MS)       0.  0.     0.        0.
  MAX BF USE (BYTES)    no limit    no limit    no limit   no limit
  BUF RESRV (BYTES)        0              0     0        0
  BUFF. REL. TIME (MS)      0.  0.     0.        0.
  NO. TRANS. Q's        1              1     1        1
  MIN PRIORITY--Q 1       1              1     1        1
  MX Q-SVC-TM (MS)--Q 1    0.  0.       0.        0.
  MAX VIRT. CKTS  no limit      no limit    no limit    no limit
FAILURE ATTRIBUTES
  TIME-TO-FAILURE (MIN)
  PROB. DISTRIBUTION     unspecified unspecified unspecified unspecified
  PARAMETER 1            0.  0.       0.       0.
  PARAMETER 2            0.  0.       0.       0.
```

```
PARAMETER 3          0.  0.       0.       0.
PARAMETER 4          0.  0.       0.       0.
STREAM               0            0    0        0
TIME-TO-REPAIR (MIN)
PROB. DISTRIBUTION   unspecified unspecified unspecified unspecified
PARAMETER 1          0.  0.       0.       0.
PARAMETER 2          0.  0.       0.       0.
PARAMETER 3          0.  0.       0.       0.
PARAMETER 4          0.  0.       0.       0.
STREAM               0            0    0        0
```

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TEST2B

CLASS-OF-SERVICE ATTRIBUTES

```
CLASS-OF-SERVICE ID CODE        _01
PRIORITY                   1
MAX HOP COUNT              3
CIRCUIT-SWITCHING ATTRIBUTES
  CALL RETRY TIME (MIN)
  PROB. DISTRIBUTION    unspecified
  PARAMETER 1           0.
  PARAMETER 2           0.
  PARAMETER 3           0.
  PARAMETER 4           0.
  STREAM                0
  BANDWIDTH REQT (KBPS)      0.
PACKET-SWITCHING ATTRIBUTES
  PKT. SIZE (BYTES)          19
  PKT. OH (BYTES)       0
  BLOCK DROPPING?       no
```

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TEST2B

DATA MESSAGE ATTRIBUTES

TRAFFIC SCALING FACTOR = 1.00

```
ORIGIN NODE ID CODE        1A
DEST. NODE ID CODE         5A
CLASS-OF-SVC ID CODE       _01
WINDOW SIZE           0
MSG INTERARRIVAL TIME (SEC)
  PROB. DISTRIBUTION  exponential
  PARAMETER 1           .6667
  PARAMETER 2          0.
  PARAMETER 3          0.
  PARAMETER 4          0.
  STREAM              1
```

```
MSG SIZE
  UNITS                 packets
  PROB. DISTRIBUTION       constant
  PARAMETER 1           1.0000
  PARAMETER 2           0.
  STREAM                0
TRIGGERED MSG DEST
TRIGGERED MSG COS
TRIG. MSG DELAY (SEC)           0.
```

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TEST2B

CIRCUIT-SWITCHING OPERATION

```
Call Preemption Enabled?           No
Call Routing Strategy              Source-Node
```

PACKET-SWITCHING OPERATION

```
Message Traffic Switching          Packet-Switched
Acknowledgement Packet Size        0
Control Packet Priority            0        (0 defaults to highest priority)
Acknowledge End of Message         No
Retransmit Interval           500        millisec
Routing Update Interval     10000        millisec
Dropped-Block Size             0        bytes
Block Dropping Thresholds          Undefined
Packet Routing Strategy            Shortest Path w/ Delay Metric
Alternate Routing Rule             Minimum Link Queue Size
Traffic Measure Type               End-to-End Delay
Max Distance Change Threshold      0        millisec
Distance Change Threshold Reduction    0  millisec
Max Flooded Packet Life           0.   sec
Virtual Call Retry Interval    60.00 sec
Max Retransmit Attempts           0
Call Request Packet Size (Bytes)      0
Call Connect Packet Size (Bytes)      0
Virtual Call Flow Control Strategy    Undefined
```

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                          TEST2B

                    ROUTING COSTS FOR CONGESTION LEVEL 1

    CIRCUIT   COS
     GROUP   _01

1A-2A   1
1A-3A   1
1A-5A   1
2A-3A   1
2A-5A   13A-5A   1

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TEST2B

CIRCUIT GROUP PERFORMANCE
FOR
PACKET-SWITCHED TRAFFIC
FROM   0. TO   30. MINUTES

CIRCUIT GROUP ID CODE	1A-2A	1A-2A	1A-3A	1A-3A
TRANSMITTING NODE	1A	2A	1A	3A
NUMBER OF CIRCUITS	1	1	1	1
BANDWIDTH LIMIT (KBPS)	2.40	2.40	2.40	2.40
BANDWIDTH USED (KBPS)				
AVERAGE	.07	.00	.08	.00
STANDARD DEVIATION	.42	.02	.43	.01
MAXIMUM	2.40	2.40	2.40	2.40
CIRCUIT GROUP UTIL %	3.09	.01	3.37	.00
FRAMES SENT	877	2	959	1
FRAMES RESENT	0	0 0	0	
PACKETS SENT	877	2	959	1
PACKET QUEUE TIME (MS)				
AVERAGE	2.71	0.	2.73	0.
STANDARD DEVIATION	10.68	0.	10.62	0.
MAXIMUM	100.16	0.	75.89	0.

CIRCUIT GROUP ID CODE	1A-5A	1A-5A	2A-3A	2A-3A
TRANSMITTING NODE	1A	5A	2A	3A
NUMBER OF CIRCUITS	1	1	1	1
BANDWIDTH LIMIT (KBPS)	.07	2.40	2.40	2.40
BANDWIDTH USED (KBPS)				
AVERAGE	.07	0.	.03	.04
STANDARD DEVIATION	.02	0.	.29	.30
MAXIMUM	.07	0.	2.40	2.40
CIRCUIT GROUP UTIL %	93.06	0.	1.45	1.54
FRAMES SENT	775	0	412	439
FRAMES RESENT	52	0 0	0	
PACKETS SENT	775	0	412	439
PACKET QUEUE TIME (MS)				
AVERAGE	136654.64	0.	0.	
STANDARD DEVIATION	123394.11	0.	0.	0.
MAXIMUM	459255.74	0.	0.	

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TEST2B

CIRCUIT GROUP PERFORMANCE

FOR
PACKET-SWITCHED TRAFFIC
FROM   0. TO   30. MINUTES

CIRCUIT GROUP ID CODE	2A-5A		2A-5A		3A-5A		3A-5A
TRANSMITTING NODE	2A		5A		3A	5A	
NUMBER OF CIRCUITS		1		1	1		1
BANDWIDTH LIMIT (KBPS)		.072.40		.07	2.40		
BANDWIDTH USED (KBPS)							
AVERAGE	.070.		.07	0.			
STANDARD DEVIATION		.020.		.02	0.		
MAXIMUM	.070.		.07	0.			
CIRCUIT GROUP UTIL %		93.130.		92.95	0.		
FRAMES SENT	828		0		826		0
FRAMES RESENT	0		0	0		0	
PACKETS SENT	828		0		826		0
PACKET QUEUE TIME (MS)							
AVERAGE		104405.060.		83723.70	0.		
STANDARD DEVIATION		85734.420.		57396.34		0.	
MAXIMUM		324864.170.		211660.03	0.		

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TEST2B

TRANSMISSION QUEUE STATISTICS
FROM   0. TO   30. MINUTES

NODE ID CODE	1A		1A		1A	2A	
CIRCUIT GROUP ID CODE	1A-2A		1A-3A		1A-5A		1A-2A
MIN QUEUE PRIORITY		1		1	1		1
PACKETS TRANSMITTED		877		959		775	2
PACKET QUEUE TIME (MS)							
AVERAGE		2.712.73	136654.64		0.		
MAXIMUM		100.185.89	459255.74		0.		

NODE ID CODE	2A		2A		3A	3A	
CIRCUIT GROUP ID CODE	2A-3A		2A-5A		1A-3A		2A-3A
MIN QUEUE PRIORITY		1		1	1		1
PACKETS TRANSMITTED		412		828	1	439	
PACKET QUEUE TIME (MS)							
AVERAGE	104405.06	0.		0.			
MAXIMUM	324864.17	0.		0.			

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TEST2B
TRANSMISSION QUEUE STATISTICS
FROM   0. TO   30. MINUTES

NODE ID CODE	3A		5A		5A	5A	
CIRCUIT GROUP ID CODE	3A-5A		1A-5A		2A-5A		3A-5A
MIN QUEUE PRIORITY	1		1	1	1		
PACKETS TRANSMITTED	826		0	0	0		
PACKET QUEUE TIME (MS)							
AVERAGE	83723.700.		0.	0.			
MAXIMUM	211660.030.		0.	0.			

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TEST2B

PACKET SWITCHING
NODE UTILIZATION STATISTICS
FROM   0. TO   30. MINUTES

NODE	1A		2A		3A	5A	
BUFFER USE (BYTES)							
AVERAGE	1149118.00		854.83		0.		
STANDARD DEVIATION		1079.83.62		655.57		0.	
MAXIMUM	4028300.00		2584.00		0.		
PACKETS PROCESSED	2668		1316		1371	2426	
PACKETS BLOCKED	3		0	0	0		
PKT SWITCH WAIT TIME (MS)							
AVERAGE	0.	0.	0.		0.		
STANDARD DEVIATION		0.	0.	0.		0.	
MAXIMUM	0.	0.	0.		0.		
PROCESSOR UTILIZATION							
PROCESSORS PER NODE		1		1	1	1	
AVG BUSY PROCESSORS		0.	0.	0.		0.	
UTILIZATION %	0.	0.	0.		0.		

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TEST2B

BUFFER UTILIZATION
BY
OUTGOING PORT
FROM   0. TO   30. MINUTES

NODE ID CODE	1A	1A	1A	2A
CIRCUIT GROUP ID CODE	1A-2A	1A-3A	1A-5A	1A-2A
BUFFER USE (BYTES)				
AVERAGE	.61 .67	1148.50	.00	
STANDARD DEVIATION	3.493.65	1079.45	.16	
MAXIMUM	57.067.00	4009.00	19.00	

NODE ID CODE	2A	2A	3A	3A
CIRCUIT GROUP ID CODE	2A-3A	2A-5A	1A-3A	2A-3A
BUFFER USE (BYTES)				
AVERAGE	.28 1117.72	.00	.29	
STANDARD DEVIATION	2.27 983.60	.11	2.34	
MAXIMUM	38.00 3420.00	19.00	38.00	

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TEST2B

BUFFER UTILIZATION
BY
OUTGOING PORT
FROM   0. TO   30. MINUTES

NODE ID CODE	3A	5A	5A	5A
CIRCUIT GROUP ID CODE	3A-5A	1A-5A	2A-5A	3A-5A
BUFFER USE (BYTES)				
AVERAGE	854.540.	0.	0.	
STANDARD DEVIATION	655.630.	0.	0.	
MAXIMUM	2584.000.	0.	0.	

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                 TEST2B

           MESSAGE DELAY STATISTICS
           FROM   0. TO 30. MINUTES

ORIGIN	DEST.	COS	MSGS BLOCKED	MSGS SENT AND RECEIVED	AVG MESSAGE SIZE IN BYTES	MESSAGE DELAY (SECONDS) AVERAGE	MESSAGE DELAY (SECONDS) MAXIMUM	% ABOVE 0. SECONDS	AVG TOTAL PACKETS	DELAY (MS)
1A	5A	_01	0	2426	19.0	109.75	463.31	100.00	2426	109745
NETWORK TOTALS			0	2426	19.0	109.75	463.31	100.00	2426	109745

NETWORK THROUGHPUT: .2 KILOBITS PER SECOND

```
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                    TEST2B

                CIRCUIT GROUP PERFORMANCE
                        FOR
                PACKET-SWITCHED TRAFFIC
                FROM    0. TO  60. MINUTES


CIRCUIT GROUP ID CODE    1A-2A          1A-2A        1A-3A      1A-3A
TRANSMITTING NODE     1A            2A             1A     3A
NUMBER OF CIRCUITS             1              1     1        1
BANDWIDTH LIMIT (KBPS)         2.402.40     2.40    2.40
BANDWIDTH USED (KBPS)
   AVERAGE              .07 .00      .08       .00
   STANDARD DEVIATION       .42 .02      .44       .01
   MAXIMUM             2.402.40     2.40      2.40
CIRCUIT GROUP UTIL %          3.09 .01     3.44       .00

FRAMES SENT          1757          6        1954        2
FRAMES RESENT          0           0    0        0
PACKETS SENT         1757          6        1954        2
PACKET QUEUE TIME (MS)
   AVERAGE            3.100.        3.30      0.
   STANDARD DEVIATION     11.220.       11.95     0.
   MAXIMUM           100.160.       96.01      0.


CIRCUIT GROUP ID CODE    1A-5A          1A-5A        2A-3A      2A-3A
TRANSMITTING NODE     1A            5A             2A     3A
NUMBER OF CIRCUITS             1              1     1        1
BANDWIDTH LIMIT (KBPS)         .072.40      2.40    2.40
BANDWIDTH USED (KBPS)
   AVERAGE              .070.        .04       .04
   STANDARD DEVIATION       .020.         .29       .30
   MAXIMUM             .070.        2.40      2.40
CIRCUIT GROUP UTIL %          95.330.       1.49      1.54

FRAMES SENT          1580          0         848      873
FRAMES RESENT         114          0    0        0
PACKETS SENT         1580          0         848      873
PACKET QUEUE TIME (MS)
   AVERAGE          192082.140.      0.        0.
   STANDARD DEVIATION   154742.340.       0.        0.
   MAXIMUM         597038.510.       0.        0.
```

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TEST2B

CIRCUIT GROUP PERFORMANCE
FOR
PACKET-SWITCHED TRAFFIC
FROM   0. TO   60. MINUTES

CIRCUIT GROUP ID CODE	2A-5A		2A-5A		3A-5A		3A-5A
TRANSMITTING NODE	2A		5A		3A	5A	
NUMBER OF CIRCUITS		1		1	1	1	
BANDWIDTH LIMIT (KBPS)		.072.40		.07	2.40		
BANDWIDTH USED (KBPS)							
AVERAGE		.070.		.07	0.		
STANDARD DEVIATION		.020.		.02	0.		
MAXIMUM		.070.		.07	0.		
CIRCUIT GROUP UTIL %		94.440.		94.25	0.		
FRAMES SENT	1678		0	1675		0	
FRAMES RESENT	0		0	0	0	0	
PACKETS SENT	1678		0	1675		0	
PACKET QUEUE TIME (MS)							
AVERAGE	162100.260.		124206.47	0.			
STANDARD DEVIATION	141071.210.		91541.95	0.			
MAXIMUM	582872.310.		409082.89	0.			

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TEST2B

TRANSMISSION QUEUE STATISTICS
FROM   0. TO   60. MINUTES

NODE ID CODE	1A	1A	1A	2A	
CIRCUIT GROUP ID CODE	1A-2A	1A-3A	1A-5A		1A-2A
MIN QUEUE PRIORITY	1	1	1	1	
PACKETS TRANSMITTED	1757	1954	1580	6	
PACKET QUEUE TIME (MS)					
AVERAGE	3.103.30	192082.14	0.		
MAXIMUM	100.186.01	597038.51	0.		

NODE ID CODE	2A	2A	3A	3A	
CIRCUIT GROUP ID CODE	2A-3A	2A-5A	1A-3A		2A-3A
MIN QUEUE PRIORITY	1	1	1	1	
PACKETS TRANSMITTED	848	1678	2	873	
PACKET QUEUE TIME (MS)					
AVERAGE	162100.26	0.	0.		
MAXIMUM	562872.31	0.	0.		

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TEST2B

TRANSMISSION QUEUE STATISTICS
FROM   0. TO 60. MINUTES

NODE ID CODE	3A		5A		5A	5A	
CIRCUIT GROUP ID CODE	3A-5A		1A-5A		2A-5A		3A-5A
MIN QUEUE PRIORITY		1		1	1	1	
PACKETS TRANSMITTED	1675		0	0	0		
PACKET QUEUE TIME (MS)							
AVERAGE	124206.470.		0.	0.			
MAXIMUM	409082.890.		0.	0.			

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TEST2B

PACKET SWITCHING
NODE UTILIZATION STATISTICS
FROM   0. TO 60. MINUTES

NODE	1A		2A		3A	5A	
BUFFER USE (BYTES)							
AVERAGE	18301031.52		1364.39		0.		
STANDARD DEVIATION		15531384.89		1279.45		0.	
MAXIMUM	60425091.00		5776.00		0.		
PACKETS PROCESSED	5367		2630		2802	4930	
PACKETS BLOCKED	7		0	0	0		
PKT SWITCH WAIT TIME (MS)							
AVERAGE	0.	0.	0.		0.		
STANDARD DEVIATION		0.	0.	0.		0.	
MAXIMUM	0.	0.	0.		0.		
PROCESSOR UTILIZATION							
PROCESSORS PER NODE		1		1	1	1	
AVG BUSY PROCESSORS		0.	0.	0.		0.	
UTILIZATION %	0.	0.	0.		0.		

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TEST2B

BUFFER UTILIZATION
BY
OUTGOING PORT
FROM   0. TO   60. MINUTES

NODE ID CODE	1A	1A	1A	2A	
CIRCUIT GROUP ID CODE	1A-2A	1A-3A	1A-5A	1A-2A	
BUFFER USE (BYTES)					
AVERAGE	.62 .69	1828.73	.00		
STANDARD DEVIATION	3.533.73	1553.39		.20	
MAXIMUM	57.087.00	6042.00	38.00		

NODE ID CODE	2A	2A	3A	3A	
CIRCUIT GROUP ID CODE	2A-3A	2A-5A	1A-3A	2A-3A	
BUFFER USE (BYTES)					
AVERAGE	1281.24	.00	.29		
STANDARD DEVIATION	21304.88	.11	2.34		
MAXIMUM	385001.00	19.00	38.00		

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TEST2B

BUFFER UTILIZATION
BY
OUTGOING PORT
FROM   0. TO   60. MINUTES

NODE ID CODE	3A	5A	5A	5A	
CIRCUIT GROUP ID CODE	3A-5A	1A-5A	2A-5A	3A-5A	
BUFFER USE (BYTES)					
AVERAGE	1364.090.	0.	0.		
STANDARD DEVIATION	1279.490.	0.	0.		
MAXIMUM	5776.000.	0.	0.		

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                        TEST2B

                    MESSAGE DELAY STATISTICS
                    FROM   0. TO 60. MINUTES

| | | | MSGS | MSGS | AVG MESSAGE AND SIZE IN | MESSAGE SIZE IN | DELAY (SECONDS) | DELAY (SECONDS) | % ABOVE 0. | AVG TOTAL | DELAY | DELAY |
ORIGIN	DEST.	COS	BLOCKED	SENT AND RECEIVED		BYTES	AVERAGE	MAXIMUM	SECONDS	PACKETS	(MS)
1A	5A	_01	0	4930		19.0	160.88	597.65	100.00	4930	160884
NETWORK TOTALS			0	4930		19.0	160.88	597.65	100.00	4930	160884

NETWORK THROUGHPUT: .2 KILOBITS PER SECOND

APPENDIX C - PACKET NETWORK STUDY

APPENDIX C - Packet Network Study

1.0 Introduction

The AX.25 Packet Network Study was a proposed and funded add-on to the original Improved HF Data Network program. The purpose of this study program was to accomplish an introductory examination of the AX.25 Protocol as used in on-the-air HF Packet Network Links.

AX.25 is an existing HF packet protocol which is used throughout the amateur and commercial radio industry. Government and Military users view AX.25 as a starting point at which more advanced, state-or-the-art packet protocols can be developed.

The investigation was a four step process:

1. Harris furnished off the shelf Amateur and Commercial grade AX.25 HF packet equipment for use within a three node HF packet network. Nodes were located at Rome Laboratories (RL), CECOM, and Harris Rochester. RL and Harris nodes were equipped with Harris RF-3200 based HF equipment. This hardware is not deliverable as part of this program, and will be returned to Harris at program completion. CECOM was supplied with Kenwood amateur HF radio equipment which will remain the property of CECOM after completion of the program.

2. All equipment was initially configured and tested for proper operation in Rochester, NY. Equipment was shipped by Harris to the other nodes to be installed by Government personnel. During the course of the program, Harris provided technical assistance for the operation and maintenance of the hardware.

3. Harris directed on-air test, and manned the node at Rochester. The other nodes were to be manned by Government personnel.

4. This appendix was written summarizing the program.

2.0 Background

The amateur Radio community has developed a packet radio protocol called AX.25 which closely resembles the CCITT X.25 data link protocol. Address fields have been expanded to

accommodate Amateur call signs and packet routing information. Binary FSK modulation at 300 baud is used for HF communication, and 1200 baud FSK is used for VHF communication. CRC error checking is used on each packet, and only error free packets are accepted at the receiving equipment.

AX.25 has become a default packet protocol for Amateur, Commercial and even some military users. Activities like the Shape Technical Centre HF Packet Radio Initiative (SHPRI) have selected AX.25 as starting point for development of NATO packet STANAGS.

Given the general acceptance of AX.25 for packet developments, it was appropriate to include it in the IHFDN program under the topic of understanding existing HF networks and protocols (IHFDN SOW 4.1.3.1). Through deployment of an AX.25 network, both the advantages (user friendly automation) and disadvantages (low performance modulation) of AX.25 could be evaluated, understood, and improved upon for the IHFDN.

3.0 Program Description

3.1 Hardware Acquisition

The HF radio and AX.25 packet equipment was readily available from Harris as well as other manufacturers. Harris acquired equipment for the three node network:

Node Location	Description	Equipment
CECOM, Ft. Monmouth, NJ	HF Transceiver	Kenwood TS-940AT
	Packer Cntrl	AEA PK-232
RL, Griffiss AFB, NY	HF Transceiver	Harris RF-3200
	Packet Modem	Harris RF-3239
	Power Supply	Harris RF-3236
Harris, Rochester, NY	HF Transceiver	Harris RF-3200
	Packet Modem	AEA PK-232
	Power Supply	Harris RF-3236

Only the amateur equipment at CECOM was deliverable as part of this program. All other equipment is the property of Harris Corporation and is to be returned at the completion of this program.

3.2 Equipment Integration

All equipment was configured and integrated at Rochester, to insure proper operation. The TS-940S transceiver was modified to allow operation outside of the amateur radio band. Backup batteries were installed in the packet modems, and they were loaded with configuration parameters. All interconnect cables were made as required. Proper operation of all hardware was verified in back to back configuration and on-air use. Installation instructions were documented.

Equipment was shipped to the CECOM and RL sites. Government personnel at the CECOM site installed the equipment with verbal assistance from Harris in Rochester as required. The RL node was not brought on-the-air for the duration of the testing. However, two additional nodes were brought into the network. These nodes consisted of:

Node Location	Description	Equipment
CRC, Ottawa Canada	500W Transceiver	Harris RF-350
	Packet Modem	AEA PK-232
Shape Technical Center (STC)	Transceiver	Kenwood TS-940
Netherlands	Packet Modem	AEA PK-232

Therefore, the operational packet network consisted of four nodes. The locations and call signs of these nodes are:

Location	Call Sign
CECOM, Ft. Monmouth, NJ	AC2XQ
Harris, Rochester, NY	XF2XEW
CRC, Ottawas Canada	VE9LBQ
STC, Netherlands	P19STC

3.3 Testing

Harris directed on-air tests from Rochester which examined the capabilities of the AX.25 protocol. Automated techniques like bulletin board services were provided so that

experimentation was performed, 24 hours a day, seven days a week, with and without manned sites.

4.0 Results

The CECOM and Rochester network nodes were brought up in early 1991. The CRC and STC nodes were added to the network during the summer of 1991. This four node network has been in operation since the summer of 1991. Various nodes have experienced outages due to manning and equipment problems. But, the basic network has been operational since this time and is planned to continue operation.

Several packet network software packages were used during the test period including bulletin board and plain terminal software. A modified public domain software package is now being used to test forwarding and data gathering functions. The program provides the data in a format compatible with spreadsheet programs. All stations are not continuous duty. There are two frequency allocation problems. However, the network usually gets connectivity for the U.S. to Europe several times per day. The path from RF Communications to CECOM provides substantially more connectivity than the transatlantic paths. However, local noise and propagation changes reduce this relatively short path to less than 100% connectivity.

4.1 Operation

The network operation consists of communications attempts once every period. A period is from 15 minutes to 60 minutes depending on the link and time of day. When connections are made, the software forwards a test message of fixed length. The typical sample test message follows the summary section.

All connection attempts are recorded in a trace file. A sample page of output from a trace file is provided after the sample test message page. As shown in this example, the calling station is KF2XEW (Harris RF Communications) and the called station is P19STC (STC). The "SABM" on each line indicates that the call is for message transfer. The "P" on each line indicates a poll frame. The mail entries on the page indicate an identifying beacon. These are unacknowledged broadcast messages notifying all nodes of the existence and active state of the KF2XEW node.

The send times, receive times, number of tries, etc. are recorded by the software. An example of a message receive file is provided after the section 5 in this appendix. The columns on this page are for date received, time received, total information frames, correlated information frames CRCX (not used), FRMX (not used), number of message bytes, elapsed time (seconds) message throughput (in bits per second) and the file name of the received message respectively.

The correlated information frames are dependent upon the message size. The total information frames include total frames that must be re-transmitted. The elapsed time is the total clock time for message transmission. The bits per second is a measure of composite on-the-air information rate. The modems that have been used for the majority of testing are running 300 baud FSK. The typical tone spacing used is 200 Hz. Some experimentation was done with other tone spacings, but 200 Hz appeared to provide good over all performance. The parameters listed on the bottom of the page include various setting for the packet node controller. These settings were determined to be most optimum for the tests and links under study.

The final appendix pages provide an example of a transmit message log. The column headings are very similar as for received messages namely date of transmission, universal time coordinates of transmission, total information frames, correlated information frames, rejections, message length (in bytes, elapsed time (in seconds), message throughput (bits per second) and transmit file name. Once again, the correlated information frames are related to the message length. The total information frames includes those that required re-transmission.

The received message information shown is for a short (<500 mile) link. As indicated, the message throughput for this link was between 60 and 120 bps. Given a data rate of 300 bps, this indicated a message throughput of approximately 30% of the link data rate. The transmit message log also provides data for a transatlantic link. The message throughput for this link typically ranges from 35 to 70 bps. Thus the throughput for this link is approximately 15% of the link data rate.

5.0 Summary

This initial packet network study has provided a significant amount of information on the viability of packet radio and AX.25 as HF communications tools. HF packet network communications were successful at all times of the day, between various locations and throughout significant changes in HF propagation characteristics. Although reduced throughputs should be expected on long haul links, the currently available HF packet equipment and protocols are able to provide reliable HF data communications under adverse conditions.

"22.09.92"	"22:55:51"	34	28	0	0	1076	91.04	94.55	"MSG0001.KI2 "
"22.09.92"	"23:10:52"	34	28	0	0	1076	108.90	79.04	"MSG0002.KI2 "
"22.09.92"	"23:28:23"	35	28	0	0	1076	96.81	88.91	"MSG0003.KI2 "
"22.09.92"	"23:46:32"	31	28	0	0	1076	135.22	63.66	"MSG0004.KI2 "
"23.09.92"	"00:03:37"	28	28	0	0	1076	71.76	119.96	"MSG0005.KI2 "
"23.09.92"	"00:20:50"	28	28	0	0	1076	76.54	112.47	"MSG0006.KI2 "
"23.09.92"	"00:39:09"	40	28	0	0	1076	145.33	59.23	"MSG0007.KI2 "
"23.09.92"	"00:56:56"	31	28	0	0	1076	92.14	93.42	"MSG0008.KI2 "
"23.09.92"	"01:14:40"	40	28	0	0	1076	109.45	78.65	"MSG0009.KI2 "
"23.09.92"	"01:26:49"	40	28	0	0	1076	147.36	58.41	"MSG0010.KI2 "
"23.09.92"	"01:30:43"	34	28	0	0	1076	96.10	89.57	"MSG0011.KI2 "
"23.09.92"	"01:38:22"	28	28	0	0	1076	96.54	89.17	"MSG0012.KI2 "
"23.09.92"	"01:53:42"	36	28	0	0	1076	125.05	68.83	"MSG0013.KI2 "
"23.09.92"	"02:10:58"	40	28	0	0	1076	131.15	65.63	"MSG0014.KI2 "
"23.09.92"	"02:28:01"	28	28	0	0	1076	118.24	72.80	"MSG0015.KI2 "
"23.09.92"	"02:44:20"	28	28	0	0	1076	72.58	118.60	"MSG0016.KI2 "
"23.09.92"	"03:01:07"	34	28	0	0	1076	102.69	83.82	"MSG0017.KI2 "
"23.09.92"	"03:17:33"	28	28	0	0	1076	81.37	105.78	"MSG0018.KI2 "
"23.09.92"	"03:33:51"	28	28	0	0	1076	72.69	118.42	"MSG0019.KI2 "
"23.09.92"	"03:51:09"	39	28	0	0	1076	133.63	64.42	"MSG0020.KI2 "
"23.09.92"	"04:07:47"	28	28	0	0	1076	92.64	92.92	"MSG0021.KI2 "
"23.09.92"	"04:38:57"	28	28	0	0	1076	72.20	119.23	"MSG0022.KI2 "
"23.09.92"	"04:57:14"	40	28	0	0	1076	125.33	68.68	"MSG0023.KI2 "
"23.09.92"	"05:13:51"	28	28	0	0	1076	91.59	93.98	"MSG0024.KI2 "
"23.09.92"	"05:30:49"	34	28	0	0	1076	113.08	76.13	"MSG0025.KI2 "
"23.09.92"	"05:47:07"	28	28	0	0	1076	72.75	118.33	"MSG0026.KI2 "
"23.09.92"	"06:03:36"	31	28	0	0	1076	84.34	102.06	"MSG0027.KI2 "
"23.09.92"	"06:20:48"	34	28	0	0	1076	118.57	72.60	"MSG0028.KI2 "
"23.09.92"	"06:37:58"	31	28	0	0	1076	125.71	68.47	"MSG0029.KI2 "
"23.09.92"	"06:55:28"	31	28	0	0	1076	135.66	63.45	"MSG0030.KI2 "
"23.09.92"	"07:11:45"	28	28	0	0	1076	72.42	118.87	"MSG0031.KI2 "
"23.09.92"	"07:28:27"	28	28	0	0	1076	89.62	96.05	"MSG0032.KI2 "
"23.09.92"	"07:44:47"	28	28	0	0	1076	73.63	116.91	"MSG0033.KI2 "
"23.09.92"	"08:02:24"	28	28	0	0	1076	91.04	94.55	"MSG0034.KI2 "
"23.09.92"	"08:19:07"	31	28	0	0	1076	84.89	101.40	"MSG0035.KI2 "
"23.09.92"	"08:35:36"	31	28	0	0	1076	85.38	100.81	"MSG0036.KI2 "
"23.09.92"	"08:52:18"	31	28	0	0	1076	83.24	103.41	"MSG0037.KI2 "
"23.09.92"	"09:09:10"	31	28	0	0	1076	84.29	102.13	"MSG0038.KI2 "
"23.09.92"	"09:25:59"	37	28	0	0	1076	102.91	83.64	"MSG0039.KI2 "
"23.09.92"	"09:42:29"	31	28	0	0	1076	83.02	103.68	"MSG0040.KI2 "
"23.09.92"	"09:59:16"	28	28	0	0	1076	74.62	115.36	"MSG0041.KI2 "
"23.09.92"	"10:15:34"	28	28	0	0	1076	72.69	118.42	"MSG0042.KI2 "
"23.09.92"	"10:43:59"	34	28	0	0	1076	121.92	70.60	"MSG0043.KI2 "

"Current system parameter settings:"

"PACLEN	=	40	MAXFRAME =	4"	
"TXDELAY	=	495 ms	TXTAIL	=	55 ms"
"PERSIST	=	255	SLOTTIME =	110 ms"	
"PTHRESH	=	0	FRACK	=	6 sec"
"CHECK	=	1200 sec	RESPONSE =	2000 ms"	
"COM PORT =	4800 baud	SREJECT	=	NO"	

"The forwarding interval was 1600 seconds"
"Forwarded data file was NOB01042"
"PMP version 3.10 (PK-232)"

"29.09.92"	"18:17:21"	60	28	2	1076	355.49	24.21	"PI9STC "
"30.09.92"	"19:14:14"	57	28	4	1076	251.43	34.24	"PI9STC "
"30.09.92"	"19:47:07"	55	28	5	1076	266.54	32.30	"PI9STC "
"01.10.92"	"16:36:29"	60	14	0	554	587.31	7.55	"PI9STC "
"01.10.92"	"18:32:16"	43	28	1	1076	229.51	37.51	"PI9STC "
"03.10.92"	"18:02:36"	4	0	0	0	103.85	0.00	"PI9STC "
"03.10.92"	"18:59:38"	34	28	1	1076	184.73	46.60	"PI9STC "
"04.10.92"	"16:25:05"	65	28	6	1076	344.56	24.98	"PI9STC "
"04.10.92"	"16:58:09"	50	28	3	1076	321.76	26.75	"PI9STC "
"04.10.92"	"18:24:37"	47	28	4	1076	195.77	43.97	"PI9STC "
"04.10.92"	"18:53:40"	33	28	1	1076	136.87	62.89	"PI9STC "
"04.10.92"	"20:20:06"	20	10	2	394	158.52	19.88	"PI9STC "
"04.10.92"	"20:48:41"	29	28	0	1076	105.77	81.38	"PI9STC "
"05.10.92"	"16:42:02"	112	24	3	954	1031.65	7.40	"PI9STC "
"05.10.92"	"18:13:17"	79	28	5	1076	358.30	24.02	"PI9STC "
"05.10.92"	"20:59:54"	51	28	4	1076	173.24	49.69	"PI9STC "
"06.10.92"	"16:35:35"	53	28	2	1076	278.41	30.92	"PI9STC "
"06.10.92"	"17:09:22"	64	28	3	1076	354.51	24.28	"PI9STC "
"06.10.92"	"17:43:26"	50	28	1	1076	286.92	30.00	"PI9STC "
"06.10.92"	"18:16:58"	48	28	4	1076	240.60	35.78	"PI9STC "
"06.10.92"	"18:47:24"	49	28	4	1076	156.87	54.87	"PI9STC "
"06.10.92"	"20:17:50"	77	28	8	1076	328.63	26.19	"PI9STC "
"06.10.92"	"20:47:48"	42	28	3	1076	150.33	57.26	"PI9STC "
"07.10.92"	"16:29:35"	75	28	7	1076	313.63	27.45	"PI9STC "
"07.10.92"	"17:01:09"	58	28	3	1076	242.31	35.53	"PI9STC "
"07.10.92"	"18:28:09"	37	28	3	1076	154.84	55.59	"PI9STC "
"07.10.92"	"19:10:34"	128	28	14	1076	606.48	14.19	"PI9STC "
"07.10.92"	"19:41:00"	38	28	3	1076	137.91	62.42	"PI9STC "
"07.10.92"	"20:12:01"	45	28	2	1076	225.38	38.19	"PI9STC "
"08.10.92"	"16:37:03"	156	12	8	474	1139.89	3.33	"PI9STC "
"08.10.92"	"18:29:49"	35	28	2	1076	102.97	83.60	"PI9STC "
"08.10.92"	"18:59:30"	43	28	3	1076	125.99	68.32	"PI9STC "
"08.10.92"	"20:25:36"	44	28	4	1076	164.23	52.41	"PI9STC "
"08.10.92"	"20:54:57"	43	28	3	1076	137.69	62.52	"PI9STC "
"09.10.92"	"18:37:08"	68	19	5	754	514.40	11.73	"PI9STC "
"09.10.92"	"19:38:52"	39	28	2	1076	125.60	68.53	"PI9STC "
"09.10.92"	"20:08:46"	52	28	5	1076	171.92	50.07	"PI9STC "
"09.10.92"	"21:05:12"	42	28	2	1076	177.31	48.55	"PI9STC "
"10.10.92"	"16:13:00"	42	28	3	1076	143.52	59.98	"PI9STC "
"10.10.92"	"16:46:19"	72	28	6	1076	354.23	24.30	"PI9STC "
"10.10.92"	"18:13:22"	51	28	5	1076	187.25	45.97	"PI9STC "
"10.10.92"	"20:59:21"	34	28	2	1076	118.90	72.40	"PI9STC "
"11.10.92"	"18:09:43"	24	2	3	74	170.27	3.48	"PI9STC "
"13.10.92"	"17:07:09"	107	28	12	1076	530.71	16.22	"PI9STC "
"13.10.92"	"19:10:52"	188	20	18	794	1187.69	5.35	"PI9STC "
"13.10.92"	"19:46:10"	84	28	8	1076	359.01	23.98	"PI9STC "

"Current system parameter settings:"

```
    "PACLEN   =     40        MAXFRAME =      4"
    "TXDELAY  =    495 ms     TXTAIL   =     55 ms"
    "PERSIST  =    255        SLOTTIME =    110 ms"
    "PTHRESH  =      0        FRACK    =      8 sec"
    "CHECK    =   1200 sec    RESPONSE =   2500 ms"
    "COM PORT =   2400 baud   SREJECT  =     NO"
```

"The forwarding interval was 1600 seconds"
"Forwarded data file was NOB01042"
"PMP version 3.10 (PK-232)"

```
NOB01042
R:910703/0817z @:PI9STC #70 <PI9STC [Staelduin, The Netherlands]
01: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
02: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
03: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
04: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
05: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
06: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
07: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
08: The quick brown fox jumped over the lazy dog's back 01234.6789 TEST DE STC
09: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
10: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
11: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
12: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
13: The quick brown fox jumped over the lazy dog's back 0123456789 TEST DE STC
```

```
[06:45:30]  KF2XEW*>PI9STC [SABM,P]
[06:58:42]  KF2XEW*>MAIL [UI]:+++ KF2XEW Development BBS / RFC Rochester, NY ++-
[07:12:01]  KF2XEW*>PI9STC [SABM,P]
[07:12:10]  KF2XEW*>PI9STC [SABM,P]
[07:12:19]  KF2XEW*>PI9STC [SABM,P]
[07:12:28]  KF2XEW*>PI9STC [SABM,P]
[07:12:37]  KF2XEW*>PI9STC [SABM,P]
[07:12:46]  KF2XEW*>PI9STC [SABM,P]
[07:12:55]  KF2XEW*>PI9STC [SABM,P]
[07:13:04]  KF2XEW*>PI9STC [SABM,P]
[07:13:13]  KF2XEW*>PI9STC [SABM,P]
[07:13:22]  KF2XEW*>PI9STC [SABM,P]
[07:13:30]  KF2XEW*>PI9STC [SABM,P]
[07:28:23]  KF2XEW*>MAIL [UI]:+++ KF2XEW Development BBS / RFC Rochester, NY ++-
[07:40:01]  KF2XEW*>PI9STC [SABM,P]
[07:40:10]  KF2XEW*>PI9STC [SABM,P]
[07:40:19]  KF2XEW*>PI9STC [SABM,P]
[07:40:28]  KF2XEW*>PI9STC [SABM,P]
[07:40:37]  KF2XEW*>PI9STC [SABM,P]
[07:40:46]  KF2XEW*>PI9STC [SABM,P]
[07:40:55]  KF2XEW*>PI9STC [SABM,P]
[07:41:04]  KF2XEW*>PI9STC [SABM,P]
[07:41:13]  KF2XEW*>PI9STC [SABM,P]
[07:41:21]  KF2XEW*>PI9STC [SABM,P]
[07:41:30]  KF2XEW*>PI9STC [SABM,P]
[07:58:03]  KF2XEW*>MAIL [UI]:+++ KF2XEW Development BBS / RFC Rochester, NY +--
[08:08:01]  KF2XEW*>PI9STC [SABM,P]
[08:08:10]  KF2XEW*>PI9STC [SABM,P]
[08:08:19]  KF2XEW*>PI9STC [SABM,P]
[08:08:28]  KF2XEW*>PI9STC [SABM,P]
[08:08:37]  KF2XEW*>PI9STC [SABM,P]
[08:08:46]  KF2XEW*>PI9STC [SABM,P]
[08:08:55]  KF2XEW*>PI9STC [SABM,P]
[08:09:04]  KF2XEW*>PI9STC [SABM,P]
[08:09:13]  KF2XEW*>PI9STC [SABM,P]
[08:09:21]  KF2XEW*>PI9STC [SABM,P]
[08:09:30]  KF2XEW*>PI9STC [SABM,P]
[08:27:44]  KF2XEW*>MAIL [UI]:+++ KF2XEW Development BBS / RFC Rochester, NY ---
[08:36:01]  KF2XEW*>PI9STC [SABM,P]
[08:36:10]  KF2XEW*>PI9STC [SABM,P]
[08:36:19]  KF2XEW*>PI9STC [SABM,P]
[08:36:28]  KF2XEW*>PI9STC [SABM,P]
[08:36:37]  KF2XEW*>PI9STC [SABM,P]
[08:36:46]  KF2XEW*>PI9STC [SABM,P]
[08:36:55]  KF2XEW*>PI9STC [SABM,P]
[08:37:04]  KF2XEW*>PI9STC [SABM,P]
[08:37:12]  KF2XEW*>PI9STC [SABM,P]
[08:37:21]  KF2XEW*>PI9STC [SABM,P]
[08:37:30]  KF2XEW*>PI9STC [SABM,P]
[08:57:25]  KF2XEW*>MAIL [UI]:+++ KF2XEW Development BBS / RFC Rochester, NY ---
[09:04:01]  KF2XEW*>PI9STC [SABM,P]
[09:04:10]  KF2XEW*>PI9STC [SABM,P]
[09:04:19]  KF2XEW*>PI9STC [SABM,P]
[09:04:28]  KF2XEW*>PI9STC [SABM,P]
[09:04:37]  KF2XEW*>PI9STC [SABM,P]
[09:04:46]  KF2XEW*>PI9STC [SABM,P]
[09:04:55]  KF2XEW*>PI9STC [SABM,P]
[09:05:04]  KF2XEW*>PI9STC [SABM,P]
[09:05:12]  KF2XEW*>PI9STC [SABM,P]
[09:05:21]  KF2XEW*>PI9STC [SABM,P]
```

APPENDIX D - INS Practicum

SUNY INSTITUTE OF TECHNOLOGY
SCHOOL OF INFORMATION SYSTEMS AND ENGINEERING TECHNOLOGY

APPENDIX TO INS FINAL PROJECT DESCRIPTION

TOPIC: SUNY INSTITUTE OF TECHNOLOGY/ROME LABS/GAFB
         HF NETWORK SIMULATION PRACTICUM

Patrick W. Fitzgibbons

BACKGROUND/PROJECT STATEMENT

As one of the full-time faculty and department chairperson of the
Telecommunications Program at SUNY Institute of Technology at
Utica/Rome, I have developed a series of network design courses
that emphasize advanced modeling and simulation techniques.
Similarly, along these lines, the communications networking branch
of Rome Labs has developed a network model/simulation that
encompasses digital voice and data communications in the high
frequency (HF) spectrum. The project described herein, is an
outgrowth of several discussions held over the course of a year
between Mr. N. Pete Robinson from Rome Labs and myself. We
proposed conducting a joint study using the combined resources of
SUNY and Rome Labs. It is within this framework that the
following project was proposed. The "INS" or Improved Network
Simulation program developed by Rome Labs, under contract to
Harris Corp., has successfully completed Phase 1 and, therefore,
this was an opportune time to conduct some further verification
and testing of the program before Phase II of the study began.
This provided the class with an opportunity to conduct a series of
simulations and comparisons with other commercially available,
analytically based modeling/simulation programs such as COMNET
II.5. The end result was further "calibration" providing an
additional level of confidence in the "INS" tool's ability to
accurately model interconnected HF nets and simulate network
quality as a dependent variable of channel cost/performance.

PROJECT DESCRIPTION

SUNY Institute of Technology at Utica/Rome offers two "upper
level" network design courses (TEL 315) Voice Network Design and
(TEL 316) Data Network Design for those students majoring in
telecommunications at SUNY IOT. Both of these courses emphasize
an applications orientation and draw upon complex "real world"
case studies allowing the students to model network consisting of
a number of independent variables and measured outcomes. The
opportunity to use a tool such as the "INS" simulation program
allowed the students to gain a much deeper understanding of the
critical role that network modeling and simulation plays within
the overall context of network design. Furthermore, the students
were able to apply several of the concepts and fundamental
principles that are developed throughout the course of the
semester as a direct result of this lab practicum.

Figure 1 . Financial Consultants International Cities

Students in the Data Network Design (TEL 316) course have the
opportunity to use a variety of sophisticated, analytically based
network design tools, as well as event driven simulation tools.
The latter category includes CACI COMNET II.5 (rel 4.5), which,
fortuitiously, turned out to be the benchmark for comparing the
INS simulation as part of the Rome Lab Phase 1 "IHFDN" project.
The Data Network Design course at SUNY makes extensive use of the
COMNET II.5 program. Comparing these complementary simulations
allowed the INS software developers to increase, by a substantial
margin, the prospective end-user's confidence level.

One of the aspects of designing data networks that was impressed
upon the students is that validating a model such as INS is
essential if the model is to have any "real world" applicability.
Although many "non-validated" models may prove sufficient for
purely academic endeavors, it is quite a different set of
circumstances pertaining to those models that are intended for use
in an actual network implementation. Consequently, it is
imperatiave that these types of models be subjected to both
extensive and exhaustive testing prior to their commercial
release. In the specific case of High Frequency (HF) type
networks the number of independent variables are numerous,
however, they are relatively stable and, therefore, lend
themselves to simulation tools like INS. The INS program is
perhaps the quintessential HF design tool, since it was
specifically designed to take into account the types of frequency
hopping and channel impairments that are characteristic of
interconnected HF nets.

Since the variables for designing HF nets and quantifying signal
transmission/reception are already well known and extensively
documented, it became a fairly straightforward task to perform the
types of comparisons that are of specific interest to the
modeler. It is these critical combinations of variables that were
addressed in the SUNY/Rome Labs study, within the framework of the
lab practicum/semester project.

Since there was no paradigm for defining the technical scope of
the project being proposed, the amount and scope of authority
given to the student by the faculty advisor largely depended on
how the lab practicum itself was organized. In an effort to
ensure this project's success the preliminary scope and mandate of
this undertaking was agreed upon by both principal investigators,
namely, Mr. N. Pete Robinson from Rome Labs and myself.

<u>CLASS SIMULATION OBJECTIVES</u>:

This class simulation focused primarily on designing a totally distributed network, using H. F. communications. In the various simulations undertaken, students evaluated the following:

- Problems that may exist in establishing high frequency data communications that are dependent upon different ionospheric conditions.

- Problems inherent in designing an operational narrowband H. F. network that spans several latitude/longitude zones.

- Analyzing the correlation between exogenous channel conditions and resulting data throughput/channel performance.

- Techniques inherent in resolving problems that involve low reliability and/or throughput on less than ideal operating conditions.

<u>FINANCIAL CONSULTANTS INTERNATIONAL - SIMULATION</u>

A hypothetical company, Financial Consultants International (FCI) was modeled for this network simulation, which consisted of three financial consulting companies. Of these three companies, one operated in Europe, one in North America, and one in the Pacific Basin. (See Figure 1)

It was assumed that each of the three original subsidiaries were using a low speed "telex-type" network service; however, each location varied in respect to the amount of traffic it generated. FCI intended to provide narrowband H. F. networking services to all its locations.

The FCI network design was modeled as follows:

In region 1, North America, the following were deemed originate locations: New York, Los Angeles and Montreal. All of the remaining NA locations are to be <u>receive only</u> destinations. The LA and Montreal nodes originated traffic to all other NA nodes, while the NY Hub also originated traffic to London and Hong Kong.

In region 2, Europe, the following were deemed originate locations: London, Paris, Rome, and Frankfurt. All of the remaining European nodes were <u>receive only</u> destinations. The Paris, Rome, and Frankfurt nodes will transmit to all other European nodes, while the London Hub will also originate traffic to NY and Hong Kong.

In region 3, Pacific Basin, the following were deemed originate locations: Sydney, Tokyo and Hong Kong. All of the remaining Pacific Region locations were <u>receive only</u>. The Sydney and Tokyo

Figure 2

FCI NETWORK
LOW DELAY
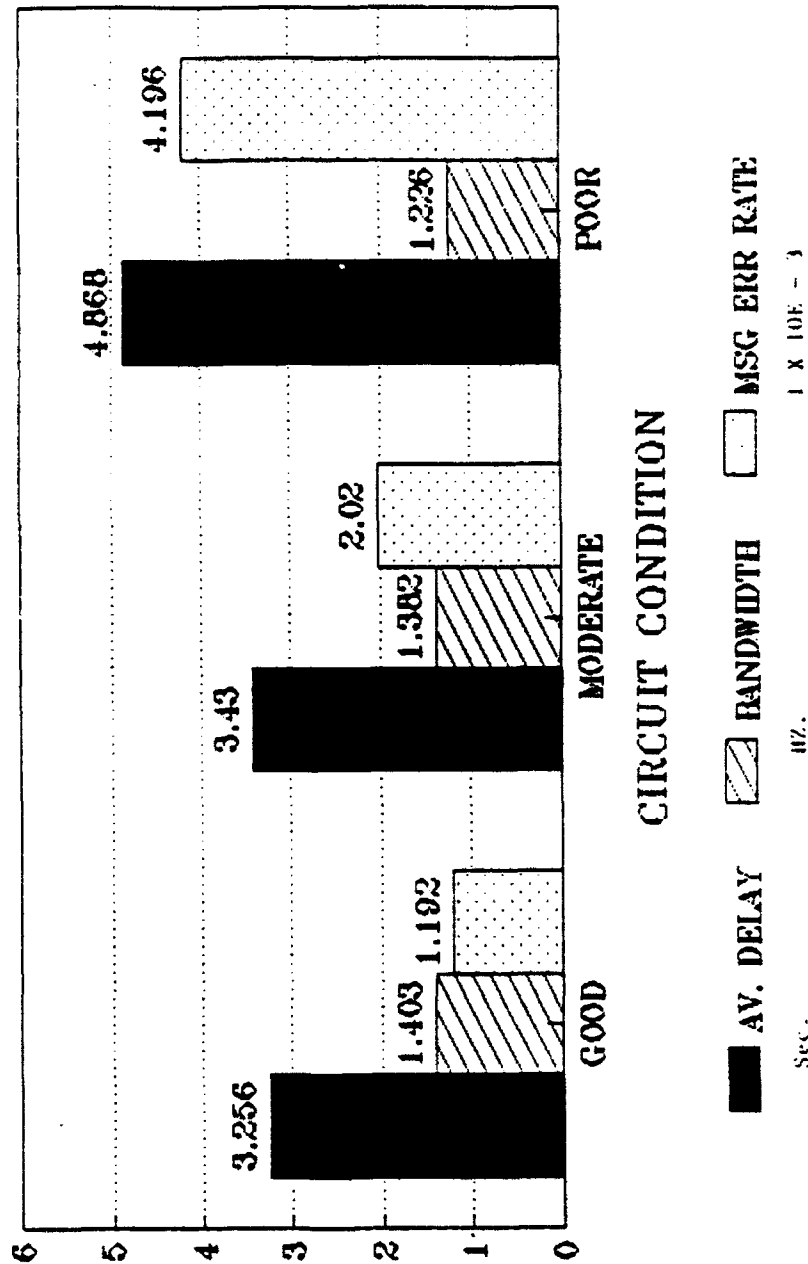
nodes transmited messages to all other Pacific region nodes, while the Hong Kong Hub also originated traffic to NY and London.

Students were required to simulate the traffic for all three Channel Performance types (e.g. Good, Medium and Poor) for the same hour/month (12:00Noon/July SSN). Each student team was assigned a separate parameter to vary while keeping these other factors constant. Students were required to graphically summarize your results using one or more types of graphs (Bar Chart, Pie Chart, XY Plot, etc.) As an example of the types of outcomes analyzed refer to Figure 2.

Network Traffic

Each originating location generated an average of 1 data call per hour to each of the terminals in their region to transfer 2 files; there are 60 seconds between transfer requests. The files average 5000 characters in length. Each office also generated 2 voice calls per day to each regional location. There are 2 to 3 minutes per call, with 20-30 seconds between calls. Each central or hub location in each of the three regions also communicated with each other at the same rate as given above.

There were 1000 data bytes per packet and 3 control bytes. There are 5 bytes of link level overhead. The node delay measurements and bit error rate performance were then analyzed.

CONCLUSION

This project allowed for a deeper understanding of the applicability of network modeling and simulation to solve "real world" problems is of great importance to enhancing the student's learning experience. This objective was accomplished while concurrently serving as a validation of the INS itself, a truly synergistic situation.

HISTORICAL TIMETABLE

The project timetable was as follows:

> Week of January 12th - the INS Software and preliminary documentation was delivered to SUNY IOT for evaluation.

> Week of January 26th - Data Network Design class commences for the Spring Semester and students are apprixed of the project.

> Week of February 10th - Mr. N. Pete Robinson visited one of the scheduled class meetings to discuss the project in terms of expectations and guidelines to follow.

Week of March 9th - Both principal investigators met to
discuss the study's progress and re-evaluate the the
project's timetable.

Week of April 12th - Preliminary results of model
simualtions/comparisons to date were analyzed and made
available to Rome Labs for preliminary feedback.

Week of April 26th - Mr. N. Pete Robinson attended one of the
scheduled classes to discuss the preliminary study findings
and address any uncertainties and the overall direction of
the project.

Week of May 10th - Professor Pat Fitzgibbons provided the
study's formal conclusions to Mr. N. Pete Robinson of Rome
Labs for evaluation.

Week of June 1st - Mr. N. Pete Robinson and Mr. P. W.
Fitzgibbons jointly presented the findings of the project and
deliver a paper addressing these outcomes at the IEEE C3
Conference.

MISSION

OF

ROME LABORATORY

Rome Laboratory plans and executes an interdisciplinary program in research, development, test, and technology transition ... support of Air Force Command, Control, Communications and Intelligence (C^3I) activities for all Air Force platforms. It also executes selected acquisition programs in several areas of expertise. Technical and engineering support within areas of competence is provided to ESD Program Offices (POs) and other ESD elements to perform effective acquisition of C^3I systems. In addition, Rome Laboratory's technology supports other AFSC Product Divisions, the Air Force user community, and other DOD and non-DOD agencies. Rome Laboratory maintains technical competence and research programs in areas including, but not limited to, communications, command and control, battle management, intelligence information processing, computational sciences and software producibility, wide area surveillance/sensors, signal processing, solid state sciences, photonics, electromagnetic technology, superconductivity, and electronic reliability/maintainability and testability.